Chapter 3

Mission Operations Functions

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We've discussed the big picture and how mission operations fits into the overall scheme. But you may still not know what space mission operators do. You're not alone—many people don't. Different countries, and indeed different organizations within a country, may organize differently to operate space missions. For example, in the United States, NASA, and DOD organize their operations differently, and people within each organization differ on philosophy and implementation. In this book, mission *operations* includes actions needed to prepare for launch, activities that take place after launch, and activities required to maintain the infrastructure that supports spare missions.

Recall that wc must distinguish between the mission concept-how the elements of the mission fit together (Chap. 1) and the *mission* operations *concept*—how we'll do mission operations to carry out the mission concept (Chap. 4). In this

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chapter we'll define the 13 functions key to mission operations everywhere and discuss how we can combine them to meet the mission operations concept. Hardware, soft ware, and people work together to complete these 13 functions. The mission operations manager (MOM) must carefully trade automation against human operations because automating some of these functions can lead to lower operations costs and, in most cases, lower life-cycle costs. Organizations may group or name those functions differently, but we believe they capture the tasks essential to mission operations.

The MOM must decide *which functions* to do, as well as their scope and *how* they'll be done. Depending on the size of the mission, a manager may even have to add functions to our list. In addition, the MOM must address organizational, hardware, and software interfaces between the functions. For example, he or she has to decide whether to use an existing mission operations infrastructure or to create one for this mission. In any event the discussion will revolve around what needs to be done and what is the most cost-effective way to do it.

Note that the 13 functions don't normally correspond to operational teams. The number and size of the operations teams depend on the mission, its complexity, and the operations organization's philosophy. For example, if we examine a communications mission using a geostationary satellite, a

- Commercial operation requires about 12 people per spacecraft to do everything
. DOD operation requires about 27 people per spacecraft to do the same tasks
- European Space Agency operation requires about 22 people per spacecraft

These examples share a common mission with minor differences in complexity and tremendous differences in philosophy, We'll examine these philosophical differences throughout this book and, in Chap. 5, we'll discuss how to assess the complexity and cost of space mission operations.

Figure 3.1 overviews a mission operations system, which implements the mission concept and mission operations concept. It processes information from, and controls, the ground and space assets, so users and operators get needed information and services. Most missions today—-science, communications, navigation, and remote sensing-focus on providing information to users or customers.

Note that we divide mission operations into two key pieces:

- *Data*—-the hardware and software on the ground and in the spacecraft that help us operate the mission
- Operations Organization---the people and procedures that carry out the mission operations concept

Mission operators should help develop the mission concept, but they often get involved too late. We intend to aggressively attack this problem in the future to

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Mission Operations System

Managing Mission Operational

Fig. 3.1.   **The 13 Functions of Mission Operations. The figure shows how the functions interact and whether they're involved in downlink (D/L) or uplink (IJ/L), Functions in the shaded area share data within the mission database.**

reduce the life-cycle costs of space missions, Mission operators *do* generate the concept that leads to successful mission operations.

Figure 3.1 and 'I'able 3.1 describe the 13 functions mission operators do for space missions. We define the functions so we can discuss them clearly. Figure 3.1 is just an example of how to implement the functions. We can combine or eliminate functions to support the desired mission operations concept. The first nine functions, shown in-the mission database box in Fig. 3.1, are basic to all space missions. We can tie them together in order to support the two essential processes for mission operations—uplink and downlink (U/1, and D/L) in the boxes. Chapter 8 discusses uplink and downlink, which operate interactively for many Earth-orbiting spacecraft. However, for a planetary mission with long, one-way light times (>10 minutes), they operate separately. The nine functions share data through the mission database and the spacecraft's avionics and require extensive data processing. The order from upper left (mission planning) clockwise to lower left reflects the usual emphasis in processing: from uplink to downlink analysis, and then to

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planning new uplink activities. The other four functions, which give us an infra-structure for mission operations, arc

- Managing mission operations
- Developing and maintaining software
- Compu ters and communications support
- Systems engineering, integration, and test

The arrows in Fig. 3.1 highlight key interactions. For example, payload data processing provides data for archiving and is a key input to mission planning. The payload data can profoundly affect mission planning, especially if we're doing an *adaptive* mission, in which operators learn from the data they see and change the mission to get different information or do other activities.

Note from Fig. 3.1 that the spacecraft and ground systems must work together on at least seven of these functions. Thus, mission operations people must take part early in decisions that divide responsibility for designing, developing, testing, and operating them. indeed, we believe mission operations should share control of spacecraft avionics to meet mission needs and constrain life-cycle costs. Key space-to-ground trade-offs in these areas are integral to the mission and mission operations concepts.

Table 3.1 lists the 13 functions and provides key issues and trades we must consider for each. We'll describe them in detail in the following sections. We'll also discuss the information required to design them, recommend a way to carry them out, and describe what they should provide--inputs, process, and outputs. Note we must do some functions, or parts of them, before launch, after launch in real time, and after launch in non-real time. Timing often depends on the mission type. For example, planning and developing activities for Earth orbiters often occurs before launch because we usually carry out these activities right after launch. But for interplanetary missions, we may develop many activities after launch--while the spacecraft is traveling to its target planet.

All 13 functions are important, and achieving mission objectives depends on parts of each. Some are also more expensive, so we must emphasize them during design to lower life-cycle costs. Table 3.2 highlights five functions, each of which consumes more than 12% of total human resources. Four of these five vary more than 6% from low to high percentages of cost. They therefore demand more of our attention to keep life-cycle costs down.

The following sections describe the information and steps needed to carry out all 13 functions, as well as the products they generate. We use background shading for post-launch activities and no shading for pre-launch activities in the tables throughout this chapter.

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Table 3.1.   Mission Operations Functions. This table shows key issues, trades, and where we discuss functions in more detail,

Function	Key Issues and Trades	Where Discussed
1. Mission Planning	• Provide positive spacecraft resource margins • Automate certain space and ground activities • Restrict the number of mission and flight rules • Focus on operability	Chap. 7,8, 14, and 15 sec. 3.1
2. Activity Planning and Development	, Reduce the required number of command loads , Automate validation of command loads and keep approval at lowest possible level , Avoid late changes to plan	Chap. 7 and 8 Sec. 3.2
3. Mission Control	, Consider sharing operations between missions or multi-tasking operators within a mission • Design ground and flight systems that can be easily upgraded • Automate analysis of ground system and spacecraft performance	Chap. 8, 12, and 15 sec. 3.3
4. Data Transport and Delivery	• Keep tracking requirements to a minimum • Design data structures and formats to use standard services • Use variable-length data packets	Chap. 11,12, and 13 Sec. 3.4
5. Navigation Planning and Analysis	• Minimize number of maneuvers "·' • Match mission requirements to accuracy of orbit determination method • Match mission requirements with standard services provided by tracking notwork	Chap. 8 and 10 sac. 3.5
6. Spacecraft Planning and Analysis	• Maintain positive resource margins • Minimize subsystem interactions • Automate spacecraft safe modes and analysis	Chap. 15 and 16 Sec. 3.6
7. Payload Planning and Analysis	• Use existing planning tools • Automate payload data gathering and calibrations • Insist on payload operability • Minimize payload operations that require knowledge of previously acquired data	Chap. 14 Sec. 3.7
8. Payload Data Processing	• Use existing tools for data processing • Address data processing requirements early in mission design • Understand need for and availability of ancillary data	Chap. 13 Sec. 3.8
9. Archiving and Maintaining the Mission Database	• Consider data push vs. data pull approach • Develop plan early and ensure capabilities exist • Understand need for and availability of ancillary data	Chap. 13 sec. 3.9
10. Systems Engineering, Integration, and Test	• Involve users, developers, and operators early in mission design • Do key trades on mission operations concept early • Maintain the big picture perspective • Use rapid development and prototyping processes	Chap. 4 and 6 sec. 3.10

Table 3.1.   Mission Operations Functions. (Continued) lhis table shows key issues, trades, and where we discuss functions in more detail.

Function	Key Issues and Tradea	Where Discussed
11. Computers and Communications Support	. Understand existing capabilities and define additional requirements .Consider maintenance and upgrades when defining system	Chap. 11 and 12 sac. 3.11
12. Developing and Maintaining Software	.Make software re-use a priority .Involve operators and users early in the design	Chap. 6 Sec. 3.12
13. Managing Mission Operations	. Implement automation and autonomy carefully • Consider multi-tasking staff . Keep organization flat and reduce interfaces	sec. 3.13

Table 3.2.   Relative Cost of Mission Operations Functions. We've compiled data for four missions and expressad the cost for each function as a percentage of the annual mission operations cost. The missions indudad are Magellan, Mars Observer, Galileo, and TOPEX. The functions highlighted with gray background use the most resources, ◢

Function	% Cost[*]		% FTE[†]	
	Low %	High %	Low %	High %
1. Mission planning	1	3	2	4
2. Activity planning and-development	4	9	7	13
3. Mission control	6	9	10	11
4. Data transport and delivery	4	9	5	11
5. Navigation planning and analysis	3	6	4	7
B. Spacecraft planning and analysis	13	20	18'''	25
7. Payload planning and analysis	3	19	33	14
B. Payload data processing	7	25	6	13
9. Archiving and maintaining the mission database	0	3	0	3
10, Systems engineering, integration, and test	3	6	3	7
11. Computers and communications support	3	9	2	5
12, Developing and maintaining software	5	8	5	8
13. Managing mission operations	9	11	11	14

' Percent of average annual mission operations costs
† Percent of annual, average, full-time "equivalents each function uses

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3.1 Mission Planning

The *mission plan* is a top-level description which spans the mission's life-cycle. It describes the way the mission will be flown, expresses objectives in operational terms, and sets in place major activities. Mission planning concentrates on uplink but takes into account the downlink abilities of the spacecraft and ground system. The mission plan is consistent with and generated after the mission and mission operations concepts. In this activity we develop mission objectives and plan how to meet them. Mission planners create a plan before launch and then change the plan as required. Before launch, mission planners play a key role in trades between mission functions. During operations, they respond to unforeseen events with updated mission plans and make sure operations meet objectives.

3.1.1   Information Required for Mission Planning

Table 3.3 lists information needed for mission planning--most during mission development. Early in development we ma y have only mission objectives, a mission concept, and a mission operations concept, We have to get the other inputs or assume them so we can begin mission planning. As a design matures, we learn enough about the mission requirements, spacecraft, and mission operations to update our plan.

Table 3.3.   Information Required for Mission Planning. Before launch, we know the mission objectives, concept, requirements, and abilities of the spacecraft (bus and payload) and mission operations system. We then compare current status and mission plan throughout the mission. Background shading indicates a post-launch mission phase, "

Information Required	Comments	Where Discussed
Mission objectives	• State in terms of science or payload return • Usually, state in qualitative terms	Chap. 1
Mission concept	• State how the mission elements will work together	Chap. 1
Mission operations concept	• Emphasize mission operations; ground systems; and command, control, and communications system • Focus on goals and vision of customer, program management, and users of payload data	Chap. 4
Mission requirements	• Make sure they are quantitative, measurable, and consistent with mission objectives	Chap. 6
Spacecraft capabilities (includes spacecraft bus and payload)	• Include capabilities of spacecraft bus • Focus on areas that are changeable to simplify operations	Chap. 14 and 15

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Table 3.3.   Information Required for Mission Planning. (Continued) Before launch, we know the
mission objectives, concept, requirements, and abilities of the spacecraft (bus and
payload) and mission operations system. We then compare current status and mission
plan throughout the mission, Background shading indicates a post-launch mission phase.

Information Required	Comments	Where Discussed
Mission operations system capabilities	• Identify current and planned abilities of the existing operations system, including tracking stations, ground stations, hardware, and software	Chap, 12
Current status versus plan (ongoing activity)	• Obtain reports from other 12 functions • Identify deviations caused by changes in spacecraft performance, customer requirements, or data requirements	Chap. 3

3.1.2   How We Plan a Mission

Table 3.4.   How We Plan a Mission. We develop a plan during mission development and change it
after launch only when spacecraft capabilities or mission requirements change,

Steps	Where Discussed
1. Quantify mission objectives and goals so they are meaningful to operators	Chap. 1
2. Define orbit or trajectory and calculate launch windows, number and" frequency of maneuvers, and viewing periods	Chap, 7; Chap. 10 [Larson and Wertz, 1992]
3. Describe the payload and define operational characteristics	Chap. 9; Chap. 14 [Larson and Wertz, 1992]
4. Describe spacecraft bus and define operational characteristics	Chap, "10 and 11; Chap. 15 [Larson and Wertz, 1992]
5. Define mission phases, allocate activities to phases, and establish a mission timeline—basis for first high-level activity plan	Chap. 7, 8, and 16
6. Evaluate requirements for operations and identify those that are "difficult to meat	Chap. 6, 11, and 12
7. Decide whether to use existing mission operations system or develop a new one	Chap. 12
8. Identify mission rules not related to health and safety imposed by program office, users, or operators and express rules in quantitative terms that software can check	Chap. 4 and 6 sec. 3.1.3
9. Document and iterate as necessary	

In mission planning we prepare the baseline set of documents described in Sec.
3.1.3. The mission plan describes how the mission will be flown until in-flight
events require it to change. The plan establishes operational criteria to meet objec-

tives, as well as major activities and events. Although planning produces a document or set of documents, it intends to understand the mission and to begin ' trading between the mission functions to get the best return for the customer's money. Much of this work begins when we're developing the mission concept.

I   After launch, mission planners periodically compare achievements to the mission plan. We learn about these achievements from payload or spacecraft planning and analysis. We then change the mission plan, mission rules, and orbital plan based on the flight system's changing abilities or processed data from the payload.

3.1.3   Products of Mission Planning

Table 3.5.   **Products of Mission Planning.** A document describing the mission plan, mission rules, and orbital phases. We complete the document during mission development and update it as needed after launch.

Products	Contains
Mission Plan	1. Mission objectives and goals 2. Orbit or trajectory description and orbital plan 3. Payload description and operation 4. Spacecraft bus description and operation 5. Mission phases 6. Description and techniques of mission operations 7. Mission rules and method of verification

The mission plan matures as launch approaches and continually reflects trades across the project's elements. The mission plan is usually placed under configuration control before the first review of project requirements. Configuration control allows changes only after everyone they affect has had a chance to review them and their costs. A proper authority decides whether or not to change the plan. Each plan contains:

Objectives and Goals. Quantify the objectives and goals of the mission so operators can understand them. For example, "discovering and understanding the relationship between newborn stars and cores of molecular clouds" is meaningful to a scientist, but "observing 1000 stars over two years with a repeat cycle of once every five months using each of the four payload instruments" is much more meaningful to an operator. Describing the objectives and goals in these terms requires experienced operators and payload users to interact. This interaction becomes very detailed while generating the mission operations concept, as discussed in Chap. 4, but the plan must include top-level objectives and goals.

Trajectory or Orbit Requirements and Description. This section establishes a context for the mission by describing the number and frequency of maneuvers, as well as constraints on the view periods of tracking facilities and target, launch time, and launch windows. (See Chap. 10)

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Payload Requirements and Description, Make sure this section includes the number of instruments and how they'll gather the data needed for the mission. Also include the payload's operational characteristics, which derive from the mission operations concept. (See Sec. 4.2.2 and Chap. 14)

Spacecraft Bus Requirements and Description. Define performance characteristics; allocate to the spacecraft mass, power, and flight information—such as memory reserve as a function of time from launch. During mission design, make sure you show the spacecraft is operable. (See Sec. 4.2.2 and Chap. 15)

Definition of Mission Phases. Define the mission phases associated with the orbit or trajectory while developing the mission concept; then, refine and modify them while generating the mission operations concept. Normally, specify the duration and function of these activities:

- Orbit insertion
- Spacecraft checkout
- Payload checkout
- Cruise (interplanetary)
- Maneuvers
- Orbit operations

'I'he orbital plan or mission-phase plan defines in more detail what takes place during each of the mission phases described in the mission plan. In describing the payload checkout phase, you may define the priority of checking out the payload instruments relative to calibrating the spacecraft's attitude-control sensors, as well as the order of checking out these instruments, The mission-phase plan reflects agreements between spacecraft and payload designers and users. It therefore defines, at a very high level, the operational activities that the spacecraft and ground will carry out during the mission timeline.

Mission Operations System Requirements and Description, Describe and include requirements for key functions. Include allocations of performance parameters by end-to-end information system (EEIS) engineering. The EEIS distributes and defines the nature of bit-error rates between the spacecraft and the ground, as well as between the ground antenna and the mission database. Most NASA missions follow standards of the Consultative Committee for Space Data Systems (CCSDS) for protocols regarding data transmission. These protocols define the way packets of information are assembled for transport. Designers of the information system must understand how packets will react to bit-error distributions, especially if the information in the packets is compressed.

Mission Rules (Guidelines and **Constrain).** Developing mission rules is key to mission planning, *Mission rules* describe how to conduct the mission and are usually not related to the spacecraft's health and safety. The health and safety rules arc called *flight rules; we* discuss them under the section on spacecraft performance and analysis. Mission rules set policy for what should be done, not for how to do it. Examples of mission rules include:

- Use a specific payload sensor only over the ocean and turn it off ten miles before crossing any land

- .**Schedule spacecraft events that require real-time monitoring during** prime shifts
- Record telemetry 15 minutes before and after critical activities.
- .**Don't overwrite critical data stored on the flight** recorder until you verify playback data.

The program office may impose mission rules, but in general they represent agreements between the users and operators of the mission operations system. Thus, **the rules** tend to depend on the mission operation team's background and experiences.

Many mission rules are checked through processes while developing and generating *activities*—a time-ordered set of contiguous events. Thus, you must quantify mission rules so operators can understand and translate them into software that can check spacecraft activities automatically for compliance with the mission rules.

3.1.4   Key Considerations

Depending on the complexity of the mission, the spacecraft, and the payload, we find that integration of engineering and payload requests can be time consuming and difficult. Complexity is a function of the

- Number of payload instruments
- .Operability of the spacecraft
- Adaptability required because of the data received from the payload instruments

Mission planners, working together with designers, may be able to lower the cost of operations by providing positive margins, automating certain space or ground functions, restricting the number of mission or flight rules, and focusing on operability.

Positive **Margins. Planners participating** in trades across the mission elements during the design phase make sure the spacecraft and instruments have positive margins. A healthy positive margin may mean we don't have to model, evaluate, and constantly monitor a spacecraft. A spacecraft designed with positive margins is easier and less expensive to operate.

An example is the power system. When the power available to the spacecraft is less than the power the spacecraft uses with all instruments and subsystems turned on, we must be very careful what we do to the spacecraft. Imagine you're at home, and you could have only half your lights, your clothes dryer or your stove, and your garbage disposal or your refrigerator on at any given time, You don't control your refrigerator, so you would have to model its performance to predict when it would be turning on and off, Then, you would have to plan to use your disposal only when the refrigerator is off, or turn off your refrigerator every time you turn on your disposal. You would also have to plan your life so you wouldn't need to dry your clothes for a dinner party at the same time you'd be

cooking dinner for that party. When positive margins exist, we don't need to pay for modeling and the tools used in modeling the spacecraft.

Earth-orbiting spacecraft typically have positive margins, Providing positive margins is more difficult for planetary missions beyond Mars, bu t we can do it. Of course these margins often reduce the scientific return of the mission, and we must trade-off operational complexity and cost against the additional scientific return,

Spacecraft Autonomy Versus Ground Generation of Appropriate Functions. Planners seldom trade well between what the spacecraft and ground units do. Often decisions are based on the cost of designing and building the spacecraft, and afterward ground operations must absorb the cost of accommodating the decision, The trade-offs include cost of making the spacecraft autonomous versus doing the same thing on the ground for the life of the mission. The mission duration is an important consideration in making this trade.

The Number of Mission and Flight Rules. Make sure you keep the mission and flight rules to a minimum during the design of the mission and the spacecraft. Each rule that must be checked involves either software or people, or both, and adds to the expense of operations.

Operability arid Interaction Between Subsystems, During the design phase and during the element trades, make the spacecraft as operable as possible and keep interactions between spacecraft subsystems to a minimum.

3.2 Activity Planning and Development

In this function wc convert each orbital-phase plan generated in mission planning into detailed commands that are ready for uplinking to the spacecraft bus as command mnemonics. Normally, we script the spacecraft's actions so each command takes place at a particular time, Many tools within the ground data system have been developed to generate these activities. Each of the NASA centers involved in flight operations has these tools. For example, JPL uses a software program called SEQGEN. Commercial packages are also available and are adequate for many missions. The next generation of spacecraft are beginning to look at process control as a way to store rules on board and to have actions occur when events satisfy these rules. These rule-based actions have usually been limited to fault-protection rules related to the health and safety of the spacecraft and payload. As the technologies mature, putting process-control rules onboard spacecraft should save operational costs and increase the payload return. Certain missions planned by NASA, such as returning asteroid samples, will require this type of onboard technology; it won't be possible to plan the spacecraft events or control them from the ground because of long delays in transmission over great distances. (See Chap. 17)

3.2.1   Information Required to Plan and Develop Activities

Table 3.6 lists the information we need. Mission planning provides most of this information for the initial activities. After launch, the mission operators' activity requests become increasingly important to achieving the mission objectives.

We also plan activities before launch for the spacecraft-.-during its integration and test phase---so wc can make sure it will work the way we expect it to work.

Table 3.6.   Information Required to Plan and Develop Activities. The mission plan (Sec. 3,1) gives us most of this information,

Information Required	Comments
Mission Plan, including the Mission Rules and the Orbital Phase Plan	.Generated by mission planning .Changes occur during the mission as the mission deviates from the nominal plan
Requests for Test and Integration Activities	.Used to support space craft integration and test . Some of these activities may occur while verifying the space-craft after launch .Comparing integration and test data to the in-flight data enables rapid understanding of the spacecraft's health
Requests for Post-Launch Activities	.Requests come mainly from spacecraft and mission control .The activity requests may have been generated before launch, but most are generated in detail after launch using building blocks, or macros of tested and validated groups of commands .The activity requests are the details which implement the higher-level plan for the orbital phase

,Payload (handwritten annotation)

3.2.2   **How to Plan and Develop Activities**

The steps for planning and developing activities, as listed in Table 3,7, provide a command load for uplink that is ready to transmit to the spacecraft. In the following pages, we'll amplify these steps. Chapter 7 provides even more detail.

Table 3.7.   How to Plan and Develop Activities. This process converts the mission plan into activities, timelines, and commands,

Steps	Comments	Where Discussed
1. Define Activities	.Next level of detail from the orbital-phase plan .Planning usually considers a series of activities, each of which relates directly to spacecraft commends .Timelines of these activities are generated .Function works closely with spacecraft and payload engineers and scientists	Chap. 7, 14, and 15 Sec. 3.2
2. Generate and Integrate Activi-ties	.Next level of detail after activity planning .Integrates new requests with the activity-planning time-line • Ensures shared resources don't conflict .Automated tools are required to do this process effi-ciently	Chap. 7 Sec. 3.2
3. Check Mission and Flight Rules	.Final check of mission and flight rules .Software helps generate activities more efficiently	Chap. 7 Sec. 3.1 and 3.2

Table 3.7. How to Plan and Develop Activities. (Continued) This process converts the mission plan into activities, timelines, and commands.

Steps	Comments	Where Discussed
4. Generate Time. lines	• The timeline displays the activities "of the spacecraft and the ground	Chap, 7 and 8 Sec. 3,2
5. Validate Activities	• Verifies the safe interaction of planned activities • Should be automated • Checks constraints for health and safety • Checks to ensure the activities do what is necessary to support the payload • Review and approval should be at the lowest possible level and add value to the process	Chap. 7 and 8 Sec. 3.2
6. Translate Activi- ties	● ""Converts the command mnemonics and associated parameters to a binary stream packaged as required by the network being used	Sec. 3.2

Define Activities, Activity planning supports payload and spacecraft-bus engineers in their early planning of the flight system. The result is one or more activities on the spacecraft and the ground needed to return certain sets of data. Each activity relates directly to many spacecraft commands. Payload-planning tools are provided that allow the payload user to superimpose the field of view of the instrument on the target body of interest. These tools correct for spacecraft trajectory, target body rotation, instrument location, boresight offsets, allowable scan platform, and mirror motion. They also provide a realistic planning footprint. As a result, an investigator can look at different ways of gathering data and determine how to set up observation patterns so they fully cover the target, Later, mission operators will carry out these activities at the right times.

Generate and Integrate Activities. Before launch, define how long it takes to generate and complete an activity. Use increments of an orbit for Earth-orbiting spacecraft, or weeks to months for a planetary spacecraft. In any event the mission phase plan lays out pre-launch priorities for the given period as the starting point for generating activities.

The Infrared Space Observatory (an ESA mission) generates a command load for seven orbits (seven days) at a time. The process is started 21 days and frozen three days before uplink. Other missions have plans tailored to their mission attributes.

New requests typically come from four functions mission control, navigation, and planning and analysis for the spacecraft bus or payload. New and unplanned requests are a part of any mission for several reasons

> ● We need an unplanned calibration (for example the star tracker, the attitude-control gyros, or the movement of a platform) to understand some unexpected data

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- Unexpected changes in the availability of tracking facilities
- The **spacecraft's abilities have changed, so all the standard** activities for a certain function need changing before the next command period
- We need to send a new set of tables up to the spacecraft based on the last calibration

These new activities may be merely executing an activity at a different time. If they're truly new, you'll have to design and test them.

Using the mission-phase plan as the baseline, take new requests from the other mission operations functions and integrate them into the command load. Remove conflicts based on rules and priorities or negotiation with the various requesters. First, integrate activity periods at a planning level and then expand these activity periods into groups of commands and individual commands. Keep integrating activities and resolving conflicts at increasing levels of detail so individual commands never conflict.

Make sure shared resources don't conflict. The desire to maximize the use of the spacecraft typically results in many activities placed close together. Late changes to activities or adding new activities can cause oversubscription of spacecraft resources such as power, time, data storage, command and telemetry links, and memory. The resource most often exceeded and hardest to resolve late in the process is time--an attempt to do too much, either on the ground or the spacecraft.

Usually, we fix allocations; that is, during a specific period, each payload instrument can use a pre-defined maximum amount of a given resource. As events begin to drive activities, we have to consider dynamic allocation of resources. Of course, we need to allocate resources only when a particular resource doesn't have enough margin. Thus, to avoid some of these conflicts, make sure resources have enough margins.

Then, ensure the margins are suitably defined, applied, and consistently enforced. If we set margins too small or use them too quickly, the uplink will be overwhelmed with conflicts, requiring last-minute deletions or rework of activities. Spacecraft commanding is one of the few areas where the final deadline is firm. If the commands aren't ready when the spacecraft needs them, there is a BIG problem—probably a complete rework of the command set while the spacecraft is idle.

Some integration occurs during mission design, We usually need to do more after the design is complete because certain information, such as final tracking schedules, may not be available earlier, or we must incorporate new activities. Many activities must happen at specific times, whereas others, such as various engineering activities, can fit in wherever possible, Except for very simple activities, you can improve integration by using automated tools that identify conflicts and missing dependencies. At this point, you'll have an integrated command load with no conflicts at the activity level. The commands are mnemonics with their required parameters.

Check Mission and Flight Rules. You can check many of the rules with the same tools used to generate the activities. But you can check other rules only after you've generated the final command load. Use software as much as possible to make activity development faster and therefore less expensive.

Generate Timelines. These timelines display at a high level—and usually in ground-received time—the activities of the spacecraft and the ground, This display allows the controllers and analysts to monitor the spacecraft's activities as the ground station receives data. This distinction isn't necessary for Earth-orbiting spacecraft, but those on interplanetary missions require it to make up for the effects of one-way delays in light time.

Validate Activities. Verify the interactions of the planned activities and make sure the command load meets the intended goals of the activities while posing no risk to the spacecraft. Automate this step as much as possible. Software tools can check to see that the command load doesn't harm the spacecraft and often visualize the sequence to make sure it gathers the information requested. Early understanding of the need and method for validation is essential to minimize the operations costs.

Because we can achieve the same end in many ways, the risk for an activity or group of activities can be difficult to quantify. Each approach has good and bad, as well as unknown, aspects. Fear of the unknown pushes perceived risks higher and drives constant searching to find a perceived "safer" way. People who know the interactions on the ground and spacecraft can accurately judge the risk without complicated analysis, but the results still must be quantified. For these reasons, projects often use hardware or software to evaluate the activity interactions. Electronic or manual reviews, hardware or software simulations, or a combination of these techniques can carry out these evolutions.

Operations are constrained for all flight and ground systems. Good spacecraft design and automation can make this task extremely easy and reduce staff. Hardware constraints (known as *flight rules*) are those which, if violated, may damage or stress a piece of the flight system, such as exceeding thermal, electrical, or radiation limits. There are obvious constraints, such as Sun impingement on a sensor array designed for viewing deep space, and less obvious constraints on the abilities of power subsystems for spacecraft in certain radiation environments. Other constraints (known as mission *rules*) provide guidelines on how to operate the flight hardware and ground systems within acceptable bounds, Violating mission rules typically won't cause permanent damage but may exceed management guidelines on effort or money expended, or compromise project goals. These rules may also set restrictions on instrument operating margins or limit operation to modes that have been tested and validated,

If you properly document constraints, you can verify compliance simply and readily automate constraint checking. Having to interpret the rules can delay the process, especially if different interpretations are supportable. For manual reviews, make statements clear, so reviewers don't need special knowledge to

understand them. For electronic reviews, make the constraints statement precise and detailed enough to convert it into code.

Because we must understand constraints early and try hard to automatically validate them, we often run command loads through simulators to make sure they're coherent and correct. We can make spacecraft simulators by setting up flight computers and flight hardware in a testbed and running the actual command load through the system. Hybrid simulators use software to simulate some of the components, such as the attitude-control subsystem. Of course, we can also build simulators entirely through software, such as modeling the flight computer in software and then running it on a workstation or other computer. But simulation costs money because we must build, operate, and check the output of the simulator. These steps require time and people.

The amount of simulation required varies tremendously within the NASA missions. We use less for Earth-orbiting spacecraft because they usually have power and telecommunication margins and round-trip transmission times of a fraction of a second. Planetary missions simulate many of their activities because they have negative margins and their data transmissions take tens of minutes to tens of hours.

Complexity of the command load and acceptable risk determine whether review and approval is long or short. Today, mission operators often risk the loss of some data and therefore shorten reviews to save money, Design each review to require the fewest people, meet technical specifications, and add to the command load's integrity. If the review is merely to have a manager sign off on the command load, you should probably eliminate the review,

Translate Activities. At this point the *command load* is in the form of words and parameters-typically called a command mnemonic for the spacecraft and some key words for the tracking net. A communal *dictionary* has translation tables to convert each command mnemonic to a binary bit pattern that is sent to the spacecraft. Translating a command load means converting activities into a format the ground transport and uplink system (such as the Deep Space Network or TDRSS) and the spacecraft can handle. For a simple flight system, this translation can convert the commands into a binary stream for ground transport and subsequent uplink. For a more sophisticated system, it can use a predicted state of the onboard memory and compile the commands into a direct memory load with required memory management.

3.2.3   Products of Activity Planning and Development

Table 3.8 describes these products. We have converted the mission plan into a series of commands or instructions that the spacecraft will execute for the next activity period. We have checked the command load to ensure that it's safe and will return the desired payload data.

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Table 3.8.   **Products of Activity Planning and Development. These three products enable the spacecraft and ground elements to operate for the next activity period**

Products	Comments
Detailed command loads in mnemonic form	.Spacecraft and payload analysts review the command loads in detail .The mnemonic form is close to an English language, in that the commands are names and parameters which relate to the command
Timeline	.The timeline graphically represents the command load, The x-axis is time, with different spacecraft, payload, and ground actions plotted in parallel against this time. .Different timelines emphasize different aspects of the mission and display at varying degrees of resolution: at minutes, hours, days, or weeks .Chapter 8 shows an example of a timeline
Commend foad	.The command load, ready for transmission to the spacecraft, is a series of bits generated as described in the translation process

3.2.4   Key Considerations

The most difficult step in planning and developing activities is avoiding conflicts while integrating the mission plan with current" requests. More complex spacecraft and planning tools, as wc]] as many automatic checks of ground data, increase this difficulty.

Larger mission margins make activity planning easier because they mean we don't have to manage and simulate resources as accurately. Spacecraft autonomy is also key; in fact, a completely autonomous spacecraft would require no activity planning and development. Finally, a mission plan that depends heavily on receiving and analyzing data to determine what to do makes activity planning and development more difficult.

To make your activity design more cost effective, follow these concepts

> . Reduce the required number of command loads. Having many command loads and dense activities within each of them will add to your staff and therefore to your budget. Whenever possible, generate command loads one after the other instead of in parallel. You need parallel generation only when the time to generate a command load is longer than time to' the execute it.

> • Validate command loads electronically and automate validation as much as possible.

> . Make sure approval of command loads occurs at the lowest possible level while maintaining acceptable levels of risk. Always ask, how does this review and approval add value?

> . Minimize changes to the command load once development starts. If mission objectives require late changes, define when they can occur and limit the amount of change at each time window. Document these constraints and make them part of the mission rules.

The speed, memory size (random access memory), and storage size (for example, hard disk space) of today's computers allows us to integrate tools for planning *and developing activities. Integrating these tools will usually automate file interfaces, make the process faster, and reduce staff.

3.3 Mission Control

Mission control runs the mission. By following a script, it directs a spacecraft's operation in real time, mainly to ensure that ground crews safely receive the required data, We use mission control whenever mission needs demand it and spacecraft tracking coverage allows it. Mission control includes carrying out the detailed activity plan and ensuring the spacecraft's health and safety during the station contact. It also means setting up and verifying the ground configuration, and then briefing everyone involved before we contact the spacecraft. Mission control then sends commands to the spacecraft, monitors its performance and that of the ground data system, and directs its recovery from any nonstandard conditions.

3.3.1   Information Required for Mission Control

We get needed information mainly from mission planning and activity planning and development. Other information comes from navigation and spacecraft planning and analysis. Table 3.9 summarizes this information.

Table 3.'9.   Information Required for Mission Control. Mission control receives information from mission planning, activity planning, spacecraft planning and analysis, and navigation planning and analysis.

Information Required	Where Discussed
Mission Plan and Mission Rules	Sec. 3.1
Command Loads and Command Files	Sec. 3.2
Real-time Telemetry	Chap. 14 and 15; Sec. 3.6 and 3.7
Tracking Schedules and Data	Chap. 10; Sec. 3.5
Pass Plan	Chap. 8

3.3.2   How to Do Mission Control

Mission control uses the information in Table 3.9, along with procedures, to operate the mission in real time. We develop procedures for spacecraft contacts, make sure data transfers take place for all uplinks and downlinks during the contact, monitor all systems during the contact, and document all activities that occur during the contact. As listed in Table 3.10, if you were on a mission-control team, you would

Table 3.10.   **How to Do** Mission Control. **Mission control develops procedures and supports integration testing before launch and directs the real-time operation of the mission after launch. Mission control supports several planning and analysis functions throughout the mission.**

Steps	Comments	Where Discussed
1. Develop Procedures for Controllers to Configure the Spacecraft and the Ground System	. Step-by-step instructions for pass support	Chap. 7 and 8
2. Support Spacecraft Integration and Test	.Verifies uplink and downlink systems .Tests end-to-end compatibility	Chap, 8, 9, and 12
3, Configure Ground System to Support Passes	.Reef-time with some pre-launch planning	Chap. 8 and 12
4. Transmit Commands to the Spacecraft	▪Done in real time during pass .Real-time commands and command loads	Chap. 8 Sec. 3.4
5. Verify the Spacecraft% Receipt of Commands	▪ Done in reaf time during pass ▪ Usually automated	Chap. 7 and8
6. Monitor the Spacecraft's Health and Safety	. Monitor telemetry in real time during the pass .Compare predicted and actual spacecraft states	Chap. 7,8, and 15
7. Monitor the Ground System Operations	.Monitor performance in real time	Chap. 7,8, and 12
8. Coordinate Mission-Control Functions	.Planning and scheduling before and after passes	Chap. 7 and 8
9. Generate an Integrated Plan for "As-Flown" Activities	. Post-pass report .Document deviations from pass plan	Chap. 8
10. Support Activity Planning and Development	. Post-1aunch support for new activities	Chap. 7
11. "Generate Operations schedules and Plans for Future Passes	. Post-launch planning and scheduling for passes	Chap. 7 and 8
12, Negotiate and Schedule Tracking support	.Coordinate with activity planning and development to generate pass plans	Chap. 8 sec. 3.5
13. Support Planning and Analysis Teams	.Help investigate anomalies	chap, 16

     1.   Develop Procedures. Controllers fly the mission using your baseline procedures. These procedures direct controllers on what to do before, during, and after a contact with the spacecraft. They cover how to configure and control the ground system and the spacecraft.

2. Support Spacecraft Integration and Test. By helping integrate and test the spacecraft bus and payload before launch, you'll see how the spacecraf t and ground system work and get hands-on training.

   You'll also do end-to-end tests, during which the ground element is integrated with the spacecraft to verify uplink and downlink. These tests validate the operations system's ability to command, deliver telemetry, and monitor alarms in real time.

3. Configure the Ground System to Support Passes. Mission controllers configure and control ground-system tools and procedures. Like the conductor of an orchestra, you use this step to make sure everything happens at the right time.

4. Transmit Commands to the Spacecraft. During the pass, mission controllers transmit scheduled real-time commands and the spacecraft's command loads. These commands are nearly always pre-planned, but procedures or oral orders may authorize mission controllers to issue real-time commands under certain predefine conditions. These predefine conditions typically cover situations in which the spacecraft has violated limits or is in a non-standard state.

5. Verify the Spacecraft's Receipt of Commands. As a mission controller, you must use spacecraft telemetry and information on the ground system's status to verify that the spacecraft has correctly received its commands. Verification is usually automatic, and detected errors produce messages and alarms.

6. Monitor the Spacecraft's Health and Safety. Monitor telemetry measurements versus alarms, the onboard memory readout and verification, and the spacecraft's predicted and actual states. Use graphical displays and text which the ground system presents to you based on processsed information from the spacecraft.

7. Monitor the Ground System's Operations. During a pass, you must monitor the ground system's performance just as you do that of the spacecraft, so the mission can meet its objectives.

8. Coordinate Mission-Control Functions. Before the pass you must coordinate some activities needed to support real-time contact . between the ground and the spacecraft. For example, you may need to

   - Schedule short-term tracking support
   - Generate an integrated plan for flight and ground activities
   - Schedule institutional support and make sure it's available
   - Generate logs and reports
   - Update databases and files

Efficient mission operations require coordination. It ensures that the ground system is able to transmit planned commands to the spacecraf t and receive, process, and store the spacecra f t's telemetry data.

9. Generate the Integrated Plan of "As-Flown" Activities, This activity plan is identical to the one prepared before the pass if everything went according to plan. But if you deviate from the plan, you must do an "as-flown" plan to record what was done and when. Typically, mission controllers use it to analyze anomalies.

10. Support Activity Planning and Development. Mission **controllers** help generate and approve the activity sequences described earlier. They typically bring to the process the interface issues between the spacecraft and the ground.

11. Generate Operations Schedules and Plans for Future Passes. To do plans for future passes, you must get ready and check out all information and data needed for the next spacecraft contact.

12. Negotiate and Schedule Facility and Tracking Support. These schedules for tracking stations become part of the activity plans described earlier in this chapter,

13. Support Planning and Analysis Teams. Help teams analyze anomalies in the spacecraft bus and payload. Experience and information from real-time controllers is invaluable to the analysts who understand the spacecraft and its subsystems but don't operate it.

3.3.3   **Products of Mission Control**

Pass plans, pass reports, database files, and alarm notices are the post-launch products of real-time operations. We list these products in Table 3.11 and describe them below.

Pass plans describe what will be done during each pass, whereas procedures describe how controllers will do it. A typical pass plan will describe the planned times for acquisition, as well as key events anticipated or required on the space-craft and the ground. It is a level higher than a command load and is used to brief everyone in the ground system before the pass.

A pass report describes the activities which took place during a contact between the ground and the spacecraft. It typically includes the commands sent, the telemetry channels that were in alarm, and any unplanned action that proce-dures or on-duty analysts authorized.

Database files generated and validated by the mission control team are the command validation files and the files or updates to telemetry and tracking data received during the pass.

When alarms occur, mission control notifies the people that their procedures identify. Although controllers have issued notices manually in the past, systems

Table 3.11. Products of Mission Control. All products are completed after launch and are related to realtime mission operations

Products	Comments
Procedures	.Describe in detail what the operators do . Describe what commands are authorized to be sent and under what anomaly conditions
Pass Plans	.Describe what is scheduled to happen during pass
Pass Report	.Describes activities which took place during a pass .Notes deviations from tha pass plan
Database Files	.Uplink-command and command-verification files .Downlink telemetry files .Ancillary data
Alarm Notices	.Alarm notices and responses occur in real time

arc now in place that beep **someone** who is on duty but not at the control center The person can then use a computer to connect with the ground system. After proper identification and authorization, this person can receive and analyze the spacecraft telemetry on his or her computer. This technology keeps teams at the control center small during spacecraft contacts.

3.3.4   Key Considerations for **Mission** Control

Mission control is easier when we can easily modify ground and flight systems to react to unplanned changes or conditions. For example, workstations and networks are more robust than a central system. Graphical user interfaces that allow operators to change configurations by point and click are easier to use than those that take lines and lines of commands.

We can lower mission control costs in several ways. Possibilities include sharing operators between missions, multi-tasking operators within a given mission, designing flexible ground and flight systems, and increasing automation in the ground system.

When several missions have common features in flight at the same time, we can train people so they may work in more than one mission at a time, thus lowering the total staff required. For individual missions, multi-tasking lowers the total staff required and makes jobs more interesting. Many of the specialists typical of early space flight now do related, but new, tasks to reduce costs.

If wc design the spacecraft to remain flexible to change, we'll need fewer resources to make these changes.

By automating analysis of the performance of the ground system and the spacecraft, we can reduce staff and probably improve performance and reliability.

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3.4 Data Transport and Delivery

This function transmits data to the spacecraft, receives data from the spacecraft, and processes tracking data. It accepts commands or command files from mission control and prepares the data for transmission, ultimately modulating the rf carrier signal and radiating the telecommands to the spacecraft. This function also captures the rf signal from the spacecraft and processes the spacecraft's engineering and mission data. Finally, it gathers and processes radiometric data used for planning and analyzing navigation. Calibration of components within this function is part of its responsibilities.

3.4.1   Information Needed to Transport and Deliver Data

Mission control and navigation planning and analysis provide information before launch to validate the system's capabilities and after launch to support real-time transmission of data to and from the spacecraft. Table 3.12 summarizes this information.

Table 3.12. Information Needed to Transport and Denver Data.
Mission control and navigation planning and analysis provide
this information before and after launch.

Information Required	Where Discussed
Antenna predicts	Chap. 10; Sec. 3.5
Binary commands or command files	Chap. 8; Sec. 3.4
Ground activities	Chap. 7, 8, and 12; Sec. 3.4
Radio frequency predicts	Sec. 3.5
Pre-track calibration data	Chap. 8 and 12; Sec. 3.4

People in navigation planning and analysis issue antenna predicts based on either pre-flight nominals or orbit determination after launch. These predicts help us point the ground-tracking or in-orbit-tracking antennas to the spacecraft during a scheduled pass. Also, if a spacecraft uses other spacecraft for orbital tracking and relay, it will have the ephemeris of these spacecraft on board and employ it to point a high-gain antenna at the tracking spacecraft during the pass.

Navigation planning and analysis generates predictions of radio frequencies (rf) and **frequency** shifts expected during each pass. Activity planners generate commands for rf transmission. Mission control then transmits commands to staff who handle data delivery and transport, Mission control also configures the ground system by using activities that setup the ground system to support passes.

3.4.2 How to Transport **and** Deliver Data

We must test and validate our approach to handling data before launch so we can be sure the spacecraft and ground system are compatible. After launch, this function uplinks commands to the spacecraft and receives and delivers the data downlinked from the spacecraft. Table 3.12 lists the steps in this process.

Table 3.13. How to Transport and Deliver Data. This process establishes our communications link to the spacecraft

Stepa	Comments	Where Discussed
1. Validate Each Function's Abilities	.Done before launch .Validates uplink and downlink tasks . Part of end-to-end test of the system	Chap. 8 Sec. 3,8
2. Send Commands to Spacecraft	.Tested before launch and carried out in real time after launch • Commands uplinked to spacecraft	Chap. 8 and 11 sac. 3.3
3. Manage Data Flow	.Tested before launch and carried out in real time after launch . Data down linked to groundstation .Standard formats recommended	Chap. 8, 11, 12, and 13
4. Determine Data Quality, Continuity, and Completeness	.Evaluates uplink and downlink data after activities are complete	Chap. 11 and 13

1. Validate Each Function's Abilities. Do me-launch steps similar to those of mission control. Test and validate facilities for'transporting and delivering data. Participate in end-to-end tests of the spacecraft to validate the uplink and downlink functions. Generate procedures used for station's setup, calibration and pass support.

2. Send Commands to Spacecraft. Telecommanding is the ground-to-spacecraft step used to instruct a spacecraft, its subsystems, or scientific instruments. To do telecommanding, you modulate telecommand data on an rf carrier. When received by the spacecraft's rf subsystem and distributed to the appropriate device, this data starts, changes, or ends an action.

Mission control supplies telecommand. Once the tracking network receives a telecommand message, determines the telecommand's destination and routes it to the appropriate tracking station (or spacecraft). Check The telecommand's format to verify that it is acceptable. Often, destination codes are reversed and the telecommand message is returned to the control center for a bit-by-bit comparison with the original. Once you've found the telecommand to be acceptable, handle it by one of these methods, one of three, predefined

Thruput telecommanding. In this mode, ~~route~~ the telecommand *is routed* immediately to the transmitting station's modulator and transmit it to the spacecraft without delay. *is routed*

Store-and-forward telecommanding. ~~Route~~ The telecommand *is routed* to a specific tracking complex together with a release time. At the appointed time, the telecommand will be modulated on the rf carrier and transmitted to the spacecraft.

~~*Telecommand radiation.*~~ Once some or all of the above steps have taken place, modulate the telecommand on a sine wave subcarrier; then, phase-modulate it on an rf carrier, amplify it, and transmit (radiate) it to the receiving spacecraft. *replace with below*

3. Manage Data Flow. This step returns information from a spacecraft to Earth-based users. Data can include the results of scientific measurements or information about the spacecraft or its subsystems. Package telemetry data to conform to one of the acceptable data formats recommended by the Consultative Committee for Space Data Systems (CCSDS). Then, encode it (optional), phase-modulate it on an rf carrier, and transmit it to a receiving tracking station or relay satellite. At the tracking station, systems or people:

Capture data. Once a tracking station's receiver is locked to a spacecraft's rf carrier, you'll demodulate telemetry data and synchronize symbols.

Extract data. Depending on whether or not coding is used and its type, there may be several times as many symbol bits as there are original data bits. To extract data, you'll need to take several typical steps. For data with convolutional encoding, use a maximum-likelihood algorithm to do convolutional decoding while detecting and correcting errors. Supply partially decoded data to a frame synchronizer, which continually tests for a unique, synchronization marker, When the synchronizer finds this sync word at successive periodic intervals, frames are synchronized, Finally, decode the Reed-Solomon block code at the end of the transfer frame correct errors before archiving transfer frames. Discard any data the system couldn't correct or, if the project requests, pass it through to the project's facility for capturing data,

Time tag transfer *frames. Once* decoding is complete and you consider the transfer frame valid, time tag the frame. For NASA, this time stamp is typically accurate to within 1.5 microseconds with respect to the time that a specific bit enters the antenna's feed horn. This time stamp appears in the secondary header of the standard formatted data unit (SFDU).

Add valued services to transfer frames, Plans predetermine how to read headers of decoded transfer frames and handle different virtual

The telecommand is then modulated on a sine wave subcarrier; then phase-modulated on an rf carrier, amplified, and transmitted (radiated) to the receiving spacecraft

channels. For example, you can return a virtual channel containing spacecraft engineering data in real time. But you may want to record a channel containing imaging data at the stations and trickle the data back as line capacity permits or mail it back. Finally, you can route a third virtual channel containing a specific instrument's data directly to the payload-processing center.

Deliver data. Finally, you must deliver the data to the project as agreed. This usually involves sending the telemetry data from the tracking facility to the project control center and populating a project or mission database. As described above, you may also send the data directly to a payload center.

Process spacecraft data. This processing is necessary if the spacecraft sends data to the ground faster than the tracking facility can send it to the control center.

4. Determine Data Quality, Continuity, and Completeness. If possible, complete this set after the pass and collect missing data from archives in the tracking station. This task is more automated now, but in most operations centers before 1992, people had to do it.

3.4.3   Products of Data Transport and Delivery

Our main products are the telemetry and tracking data collected during a pass. We also produce reports on tracking passes and on the quantity, quality, and continuity (QQC) of stations.

Table 3.14. Products of Data Transport and Delivery. We generate these products in real time during a station pass and when time permits following a station pass.

Product	Comments
Telemetry data	• Generated in real time during station pass
Tracking data	• Generated in real time during station pass
Tracking pass report	• Post-pass, when time permits • Generate with mission control
Station QQC reports	• Post-pass, when time permits

We process the telemetry data as described in Chap. 13 and Step 3 above and then deliver it into the projector mission database.

Tracking data, also defined as radiometric data, is used to determine a spacecraft's position as well as for scientific investigations. These data quantify the relative position or motion of the spacecraft and the Earth. Several types of data are available:

- Doppler data
- Ranging data
- Angle data
- Very long baseline interferometry
- Radio science measurements

Station pass reports typically capture the configuration of the tracking station or spacecraft during the pass and concentrate on deviations from normal conditions. We list these reports as a project deliverable and include them in the' mission database,

Station QQC reports describe the quantity, quality, and continuity of the telemetry gathered for the project during the contact. They include the statist ics on both the real-time data and the high-rate data received but not necessarily processed during the pass. Most networks include this information electronically, but we also deliver it to the project database,

3.4.4   Key Considerations

Network loading and out-of-date systems cause most of our problems in handling data. For example, sending data from the tracking stations to the control centers with protocols of the 1970s causes errors in the mission database. NASA developed these protocols before commercial standards were in place. Now, we need to follow CCSDS standards or those of the network tracking our spacecraft, or we'll have problems getting standard services.

We can reduce the cost of the handling data by first keeping tracking coverage to a minimum. Tracking consumes resources from every part of mission operations. Overloaded tracking networks already have trouble allocating these resources to space projects.

Next, we can design structures and formats for flight data to match the abilities of our transport and delivery system. Using standard services is reliable and cost effective, Having an engineer design a new spacecraft characteristic to enhance a mission may result in spending a lot of money on developing and operating ground systems that must support this characteristic,

Finally, we should use variable-length packets instead of many unique, predetermined formats. Today's standards and technology allow us to identify a data packet's length in the header, so we don't need to use inefficient fixed-length packets,

3.5 Navigation Planning and Analysis

We must determine the spacecraft's position and predicted flight path, as well as how to correct that flight path to achieve mission objectives. To do so, we must

- Acquire radiometric tracking or optical measurements

- Determine the statistically best estimate of the trajectory based on these measurements
- Compute trajectory-correction maneuvers (TCMs) to achieve the desired targeting objectives or orbit changes
- Plan and analyze performance to ensure it meets mission and payload objectives

3.5.1 Information Needed to Pian and Anaiyze Navigation

Because determining and predicting spacecraft orbits is uncertain, we must continually update our estimate of the spacecraft orbits by analyzing tracking data. We also have to know the locations of other celestial bodies, such as the Sun, Moon, or Jupiter, to predict their effects on the spacecraft's trajectory. Finally, when orbital maneuvers are necessary, we must have an accurate model of the spacecraft propulsion system to plan the maneuver. Table 3.12 summarizes these requirements.

Table 3.15. Information Needed to Plan and Analyze Navigation. We need this information to determine and predict orbits, as well as to plan spacecraft maneuvers.

Information Required	Where Discussed
Ephemeris data of celestial bodies	Chap. 10
Planetary atmospheric and dynamic models	Chap. 10
Tracking data	Chap. 10; Sec. 3.4
Information on spacecraft propulsion	Chap. 15; Sec. 3.6

3.5.2 How to Pian and Analyze Navigation

We must convert raw tracking data to current and future estimates of the spacecraft's orbit or trajectory. We also calculate the maneuvers necessary to maintain our spacecraft orbit or change the orbit to meet fission objectives. We've listed steps in Table 3.12 and described them below.

Table 3.16, How to Plan and Analyze Navigation. We statistically combine tracking data to estimate the current orbit and then use this estimate to generate trajectories and plan maneuvers.

Steps	Comments	Where Discussed
1. Support Pre-Launch Mission Planning	• Demonstrate the orbit propagator's abilities	Chap. 10 Sec. 3.1
2. Determine Orbit(s)	• Statistically determine best estimate of orbit using tracking data, onboard data, or other sources	Chap. 8 and 10

Table 3.16. How to Plan and Analyze Navigation. (Continued) We statistically combine backing
data to estimate the current orbit and then use this estimate to generate trajectories and
plan maneuvers.

Steps	Comments	Where Discussed
3. Design and Analyze Maneuvers	.Use to maintain and modify orbit	Chap. 10
4. Determine and Plan Spacecraft Attitude	• Done with spacecraft planning and analysis . Combine with position information to accurately determine pointing information	Chap. 10 and 15
5. Generate and Regen- erate Trajectories	.Use to generate future spacecraft location predic- tions	Chap. 10

1. Support Pre-Launch Mission Planning. Use predictive tools and other tests to show the navigation equipment can do what the mission requires.

2. Determine Orbit. Extract radio-tracking data (Doppler, range, range-rate, and VLBI) at the tracking stations, transmit it over high-speed data lines to the control center, and buffer it on computer-disk storage. Newly acquired data of different types from individual tracking stations for various spacecraft are automatically sorted and merged into a single time-ordered array for the spacecraft of interest. After **removing data of poor quality, you have** a data file ready for orbit determination.

   Chapter 10 explains this process in detail. Missions are experimenting now with Earth-orbiting spacecraft that can use onboard GPS receivers and reduce or eliminate the need for radiometric tracking data. This is an example of moving the function completely inside the avionics part of the mission operations diagram (Fig. 3.1).

3. Design and Analyze Maneuvers, Propulsive maneuvers are required to maintain a spacecraft's orbit and to navigate a deepspace mission to its target. Before launch, determine how to place these maneuvers to satisfy mission objectives and operational constraints while using as little fuel as possible. During the mission, factor in the spacecraft's actual performance, To make future maneuvers more accurate, analyze each maneuver to improve orbit determination and the spacecraft's performance. Chap. 10 discusses spacecraft maneuvers in more detail.

4. **Determine and Plan Spacecraft** Attitude. For missions which require the spacecraft to point at an object on Earth, in space, or on the surface of another planet or asteroid, you need a predictive tool to help generate commands. People handling the spacecraft or payload

usually operate these tools, but you give them information on the spacecraft's attitude and the payload's pointing direction, By calculating these values, you give payload users inputs that are more accurate than the predicts used to generate the commands.

5. Generate and Regenerate Trajectories. Each time the orbit or trajectory is updated, you must do new predicts, which are used by nearly everyone in mission operations. Onboard the spacecraft, they help us point the payload instruments, antennas, and communications.

3.5.3   Products of Navigation Planning and Analysis

Accurate, post-launch predictions of the spacecraft's trajectory, required maneuvers, and at tit ude history make the products listed in 'Table 3.17 important to other mission operations functions, especially in mission planning and data processing.

Table 3.17, Products of Navigation Planning and Analysis. Products are generated post-launch and used as inputs to other mission operations functions.

Product	Comments
Trajectories (past, present, and future)	.Input to data processing, mission planning, and mission control
Maneuver designs ""-	.Input to spacecraft planning and analysis and mission planning
Attitude history	.Input to data processing

3.5.4   Key Considerations

Accuracy drives the cost of orbit determination. We have to make sure the mission needs certain levels of accuracy before spending money on navigation systems that must support them.

Having fewer propulsive maneuvers simplifies navigation because we must plan them and then determine and analyze new orbits or trajectories after each maneuver is complete.

After selecting a tracking network, we should try to match our mission requirements to their standard services for determining orbits and predicting trajectories. Sometimes, we can change our requirements so they're compatible with the network's services.

Because onboard computational abilities and supporting technologies are improving, we must understand the cost and accuracy trade between determining orbits and propagating trajectories onboard versus doing the same things on the ground. GPS's capabilities to support onboard navigation may well be sufficient for many LE() missions.

3.6 Spacecraft Planning and Analysis

Here, planning and analysis make sure wc maintain the spacecraft's health and safety and get back its mission and scientific data. Spacecraft engineers

- Prepare telemetry predictions
- Analyze the real-time and processed data
- Identify and resolve anomalies
- Design maneuvers
- Maintain attitude-control and flight software
- Develop, analyze, and test the engineering commands for uploads and real-time commanding

Spacecraft engineers also use the analysis soft ware and hardware (testbed) on the ground to analyze data, prepare predicts, and simulate commands. Finally, they maintain and update various documents or databases (dictionaries, maps, procedures, flight rules and constraints, plans) and reports (consumables, trends, and in-flight performance) needed to complete a space mission.

3.6.1   Information Needed to Plan and. Analyze a Spacecraft

To do this function, we get inputs from the five previously discussed mission operations functions: mission planning, activity planning and development, mission control, data transport and delivery, and navigation planning and analysis. The information describes how we expect the spacecraft bus to operate, the space-craft bus's actual performance, and the spacecraft's upcoming maneuvers and planned activities. We need telemetry data, plans, and activities before launch to validate the spacecraft bus's capabilities and all five inputs after launch to plan the spacecraft bus's activities and anal yze its performance. Table 3.12 summarizes this information.

Table 3.18. Information Needed to Plan and Analyze a Spacecraft. We get information needed to plan and analyze spacecraft-bus operations from previously described functions.

Information Required	Where Discussed
Plans	sec. 3.1
Command files	Sec. 3.2
Alarms and pass reports	sec. 3.3
Channelized telemetry data	sec. 3.4
Maneuver designs	sec. 3.5

3.6.2 , How to Plan and Analyze Performance of a Spacecraft

In this function wc compare the spacecraft bus's actual performance with the expected performance to make sure it meets mission objectives. Many of the steps listed in Table 3.19 begin before launch, and all but the first step, validation, continue until the end of the mission. We further describe these steps below.

Table 3.19. How to Plan and Analyze a Spacecraft. Steps are not necessarily sequential. We do them as needed before-and after launch to maintain the spacecraft's health and safety and ensure we get back all mission data

Steps	Comments	Where Discussed
1, Validate Processing Abilities of the Spacecraft and Ground Data System	.Done before launch during end-to-end tests of the system .Helps train operators	Chap. 12 and 15
2. Generate Reports and Maintain Database	.Reports describe the spacecraft bus and its operation .After launch databases document actual performance	Chap. 15 Sec. 3.1 and 3.4
3. Plan Calibrations	.Prelaunch planning of calibrations .Post-launch updates based on spacecraft performance	Chap. 7 and 15
4. Generate Reports on Consumables, Trends, and Performance	.Compare actual arid expected performance of spacecraft hardware and resources	Chap. 15
5. Plan Spacecraft Bus Commands	. Generate all commands uplinked to spacecraft bus • Coordinate with mission planning and activity planning and development	Chap. 15 Sec. 3.1 and 3.2
6. Operate end Maintain the Flight Simulator	• Usad to verify command loads before uplinking commends to spacecraft	Chap. 8 sec. 3.3
7. Maintain the Spacecraft Bus's Flight Software	• Manage flight software .Generate software memory loads . Control software configuration	Chap. 15 Sec. 3.12
8. Analyze Engineering Data	.Determine health, safety, and performance of spacecraft .Investigate spacecraft anomalies	Chap, 15 and 16

> **1. Validate** Processing Abilities of the Spacecraft and Ground Data **System.** Before launch, test and validate the ground processing system and its compatibility with the spacecraft. Show compatibility mainly through end-to-end testing, with the spacecraft and ground station flowing data into the control center. Often, you'll do these tests while the spacecraft is in the thermal-vacuum chamber.

You can also participate in spacecraft system tests to ensure that the part of the ground system used for spacecraft planning and analysis is operating properly. This step also best trains people in mission operations on the spacecraft's characteristics before launch.

2. Generate Reports and Databases. Include:

| *Flight rules and constraints,* List all in-flight operational limitations imposed by the spacecraft hardware and software.

| *Decommutation maps.* List the telemetry channels contained in each of the different maps, which define the variable part of the telemetry commutator. Nearly all missions are now using CCSDS standards which define packets of information. Each packet is self identifying and, when used properly, replaces decommutation maps.

| *Telemetry dictionary.* Describe in detail the engineering and science telemetry measurements, as well as the operational limits and parameters needed to understand each measurement,

| *Command dictionary. Describe* and show bit patterns of the messages and commands **that may be sent to the spacecraft; cross-reference the flight** rules and telemetry dictionary,

| *Spacecraft* idiosyncrasies. Include unusual or anomalous performance characteristics.

| Operating *procedures.* Define how to do spacecraft planning and analysis.

| *Spacecraft contingency plan.* Identify potential anomalies that would require ground response and plan corrective actions.

| 3. Plan Calibrations. Show the strategies and activities for calibrating subsystems of the spacecraft that affect its performance. Subsystems you must usually calibrate after launch (and sometimes during the mission) include attitude control, star trackers, and moveable platforms.

4. Generate Reports on Consumables, Trends, and Performance, Periodically identify uses, changes with time and operation, and performance of the spacecraft. Although you'll do most of this after launch, start reporting during the system test and then maintain and update reports during the mission.

5. Plan Spacecraft Bus Commands. Generate all command inputs and review all system commands for uplink to the spacecraft. Command | requests (planned real-time and command loads) are to calibrate spacecraft subsystems and maintain the spacecraft's health. Review | planned command uploads for correct engineering and completeness.

Develop maneuver designs using inputs from navigation planning **and analysis and determine appropriate commands to carry out the**

maneuver. In the future, the ground system may transmit a new state vector to the spacecraft, which would then compute and execute the maneu ver. If so, detailed ground commands won't be necessary.

Spacecraft planning and analysis supports mission planning and activity planning and development as required during the mission.

6. Operate and Maintain the Flight Simulator. A flight simulator (such as a testbed, simulator, or testlab) is often required to verify commands before radiation to the spacecraft.

7. **Maintain the Spacecraft** Bus's Flight Software. Maintain flight software, generate memory loads for this software, and control all changes to flight programs, including databases.

8. Analyze Engineering Data. Analyze the spacecraft's engineering data (real-time and non-real-time) and determine its health, safety, and performance. Develop performance models before launch. These models may be software programs or hardware models that predict the spacecraft's performance and analyze its data. Assess performance by analyzing the spacecraft's system data. Investigate spacecraft anomalies and correct them. Help investigate payload anomalies as requested. Maintain trends and supply information to mission planning about the spacecraft's deviations from pre-launch assumptions of its abilities.

3.6.3 Products of Spacecraft Planning and Analysis

We use the products from this function to develop future spacecraft requests. We coordinate with mission control, mission planning, and activity planning and development to schedule necessary commands during future spacecraft passes. We also use the products listed in Table 3.2'0 to support payload planning and analysis and data processing,

Table 3.20. Products of Spacecraft Planning and Analysis, We complete these products after launch and input them to other mission operations functions.

Product	Comments
Spacecraft status versus plan	.Generate post-launch .Use to track performance and modify mission plan
Spacecraft limits	.Generate pre-launch and update post-launch based on actual performance
Spacecraft activity requests	.Generate pro-launch and update post-launch .Input to mission control
Processed spacecraft data	.Generate post-launch .input to payload planning and analysis and date processing
Reports	◄ See Step 2 for a list of the most important reports

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3.6.4 **Key Considerations**

The key driver of operational complexity is the level of resource margins available on the spacecraft. A large positive power margin means we don't need detailed analysis of planned activities. If there is a negative power margin with all spacecraft and payload sources on, analysis becomes more difficult and detailed. If subsystems interact under negative margins, spacecraft planning and analysis becomes even more difficult.

Other factors are level of spacecraft analysis required, number of interactions, spacecraft safing, the need for real-time engineering analysis, and the level of automat ion available. Properly designing the spacecraft and the associated telemetry measurements will make it possible to analyze the spacecraft system. There is still a tendency to design the "best" subsystems, integrate them into a spacecraft, and then attempt to figure out how to analyze the spacecraft in flight. This approach will usually mean analyzing each of the subsystems for proper operation and then integrating this information at the system level. Subsystem analysis of a spacecraft is labor intensive.

The spacecraft that minimizes interactions between spacecraft components, between spacecraft and payload components, and between payload components will be easier to operate and require fewer resources from planning and analysis.

A spacecraft that will go to a safe state when an error occurs is easier to operate than one that is fragile and needs a lot of monitoring.

Many of today's spacecraft can go unattended for a week or more at a time, but operators tend to want to observe and monitor the spacecraft in real time. Frequent real-time operations require more resources than real-time passes once a day or once a week.

Finally, using automated analysis tools to decrease staffing lowers operations costs. Artificial-intelligence techniques are now becoming useful for mission operations.

3.7 Payload Planning and Analysis

We need to identify and prioritize payload opportunities in order to design observations and activities and to correctly carry out the command load transmitted to the spacecraft. We analyze payload data to assess the payload's performance and to change planned observations when necessary to get better data.

3.7.1 **Information Needed to Plan and Analyze Payload**

We get information from mission planning, activity planning and development, mission control, and data transport and delivery. We use it before launch to make sure the payload is operable and the data system is compatible, After launch, the information helps us assess the payload's performance and plan observations. Table 3.21 lists the inputs for this function.

Table 3.21.   **Information Needed to Plan and Analyze a Payload. We need information before launch to validate payload operability and after launch to plan observations and assess performance.**

Information Required	Where Discussed
Plans	Sec. 3.1
Activities	Sec. 3.2
Alarms and pass reports	Sec. 3.3
Payload data	Sec. 3.4

3.7.2   How to Plan and Analyze a Payload

Table **3.22** lists the steps for payload planning and analysis. Before launch, monitor the design and development phases to ensure you have a payload operations concept that will work and meet mission objectives. After launch, monitor the payload performance, help plan future operations, and plan necessary payload calibrations.

Table 3.22. How to Plan and Analyze a Payload. These steps are similar to those done in spacecraft planning and analysis. They focus on the payload's proper and accurate operation.

steps	Comments	Where Discussed
1. Validate Processing Abilities of the Payload and Ground Data System	• Conduct pre-launch during end-to-end tests of the spacecraft • Helps train operators	Chap, 12 and 14
2. Generate Reports and Databases	• Write reports pre-launch with mission planning • Maintain databases post-launch	chap. 14 Sec. 3.1 and 3.4
3. Plan Payload Observations	• Identify opportunities • Assign priorities and resolve conflicts • Generate and validate command loads	Chap, 7 and 14
4. Plan Payload Calibrations	• Use to correctly interpret data • Use for calibrations based on analysis of payload data	Chap. 7 and 14
5. Analyze Payload Performance	• Quick-look analysis • Calibration analysis • Trend analysis	chap. 14
6. Assess and Maintain Payload Flight Software	• Manage payload software • Generate software memory loads • Control configuration of payload software	chap. 14 Sec. 3.12
7. Investigate Anomalies	• Do as required • Support spacecraft planning and analysis	Chap. 16

1. Validate Processing Abilities of the Payload and Ground Data System. Before launch, these activities arc much like those for spacecraft planning and analysis. You will usually participate in the same tests as those described for the spacecraft. A key difference is that some of the instruments may not be turned on, except during the thermal-vacuum testing with its simulations of space environments.

2. Generate Reports and Databases. Similar to those for spacecraft planning and analysis.

3. Plan Payload Observations. Identify payload opportunities by evaluating trajectory information and the ephemerides of the body being investigated, be it Earth or a planet. These opportunities represent times in the mission during which the payload's observations will achieve mission objectives. Once opportunities have been identified, design, implement, and integrate these observations to form the command load and transmit it to the spacecraft. Depending on the payload, you may divide the observations into discipline groups, so that each discipline group identifies observations to meet the mission's objectives. If the payload has only one instrument, this process is considerably simpler than if it has a dozen instruments. Each discipline group then prioritizes its observations and activities.

Once priorities are set, combine into a single file the inputs from each group and the observations requested from the payload and spacecraft engineering disciplines. Priorities help resolve conflicts between the discipline groups and produce a conflict-free timeline of activities that will generate commands for the spacecraft and instruments. The degree to which this process can be automated varies with mission and spacecraft design. At NASA, mapping missions are highly automated because mapping strategies are automated and observations don't require decisions. The astrophysics community uses a very automated process to determine observations for each orbit. On the other hand, planetary missions tend to require a lot of interaction and many human decisions.

Payload planning often begins months or even years before final command load goes to the spacecraft. As such, observations may need changing to account for discoveries or new information about the observation. Thus, the ground system allocates resources (people, hard ware, and spacecraft) to these changes. For essential observations, you can also slightly modify the command load onboard the spacecraft.

Payload planning ends when you validate internal commands for the spacecraft and instruments. Base these commands on scientific needs, the spacecraft's abilities, and mission guidelines and flight rules.

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Submit commands to activity planning and development, where people will expand, constraint-check, and compile them. Then, validate them again to ensure the final commands don't harm the spacecraft and accurately reflect the initial observation requests.

4. Plan Payload Calibrations. You need calibrations to correctly interpret the payload data. First, analyze the payload telemetry during downlink and then design and do changes to the calibration plan, or do more calibrations, to ensure accurate processing and interpretation of the received data. Early definition of this process during payload design reduces the time you must spend on calibration.

5. **Analyze** Payload Performance. Operate and calibrate the payload hardware and analyze trends, This step ensures the instrument is within specifications and no trend is developing that would keep it from meeting future demands.

To analyze the payload, you can do

Quick look analysis. Inquire into the health and quality of the instrument data.

Calibration analysis. Analyze calibration observations and selected observations by the instrument. If necessary, ask for new calibration observations or even a change to the basic calibration plan written before launch.

Trend analysis. Analyze mainly the engineering measurements on the instrument that show the health and performance trends during the mission. Note carefully anything that suggests you must change the instrument's operating plan.

6. Assess and Maintain Payload Flight Software. Many of the instruments flown today have processors as large as the spacecraft's processors. Maintain this software just as you would the spacecraft's software.

7. Investigate Anomalies. Do these as required and help the spacecraft group analyze spacecraft anomalies as appropriate.

3.7.3   Products of **Payload** Planning **and Analysis**

As with spacecraft planning and analysis, products from this function help mission planning and mission control plan and conduct future operations. Table 3.23 lists these products.

Table 3.23. Products of Payload Planning and Analysis. Products are inputs to mission planning, mission control, and data processing.

Product	Comments
Payload status versus plan	• Input to mission planning • Use to monitor payload performance
Payload limits	• Input to mission planning and mission control
Payload activity requests	• Input to activity planning and development
Processed payload data	• Input to payload data processing

3.7.4   Key Considerations

The spacecraft and data-handling enable us to get payload data to the user for planning and analysis. When these systems introduce errors or don't meet specifications, we must reevaluate payload planning and often change it to solve these problems. We must also do more payload planning when the mission plan asks us to generate payload activities based on analysis of received data. When the ground system has to be more adaptable, mission operations costs go up.

To reduce these costs, use existing planning tools, automate payload datagathering, emphasize payload operability during design, and minimize required adaptivity of the payload in the operations concept.

Many planning tools exist, and others are "new" designs of present capabilities. We tend to r-e-invent capabilities instead of finding tools we can use "as is" or with slight changes.

Next, consider automating the payload data-gathering and calibration. Onboard automation of data-gathering reduces the resources required to operate the payload but usually demands resources up front for planning the automation,

Keep insisting on payload operability during the design phase. Ask questions of the instrument builders: "How are the instrument commands going to be determined? What information is required, and how is this information converted into instrument commands?" Make sure the team add resses the number and complexity of calibrations before completing the payload design.

Finally, minimize the amount of adaptivity required to achieve mission success. A mission that requires information from the payload before the next command load can be generated is more expensive to operate than one that collects data in a standard manner. Adaptivity is sometimes necessary but designers often use it to put off understanding how to establish observations or command loads,

3.8 Payload Data Processing

First, we must bring together instrument data packets, engineering data, and ancillary data (e.g., orbital /navigation data) into instrument data records. We may also need to do higher-order processing to support payload analysis and generate

digital and photography products of archival quality. In fact, wc may need to do any of the processing steps described below-at either the control center, a dedi-
I   cated payload-processing facility, or on the spacecraft.

The soft ware for processing payload data is often unique (not commercially available) because specialized routines are required for some scientific processing that has few commercial customers. Examples include

- .Cartographic projections for bodies other than the Earth
- •Radiometric reconstruction of **color** imagery from multiple images acquired through spectral filters
- •Image registration to less than one pixel accuracy

After this--and perhaps more specialized---processing, the data is ready to be archived for use by other scientists in the case of NASA missions. Chapter 13 further discusses processing of payload data.

As mentioned earlier, processed payload data may change the mission plan, but at this processing level, we usually pick up very subtle but important instrument characteristics.

3.8.1   Information Needed to Process Payload Data

Table 3.24.   Information Needed to Process Payload Data. To process payload data, we need it plus other data regarding the spacecraft and ground system

Information Required	Comments	Where Discussed
Payload data	• Payload data in the form sent to the spacecraft avionics system (usually packets) is received by payload date processing • Instrument-1evel testing, payfoad integration testing, spacecraft integration testing, and flight data all make up the payload date	sec. 3.4
Ancillary data	•Ancillary data is information about the spacecraft and ground system required to properly process and analyze the payload data •The specific data and the formats ara specified before launch. These data include "spacecraft and payload engineering information.	sec. 3.4
Orbital/navigation/ attitude-predict data	• This date is sometimes included as ancillary date but is important enough to be called out separately ◄ Most observations require information relative to where the payload is pointing to be able to interpret the data. .Sometimes, as information about the orbit or trajectory improves, it may appear in several versions, which we must be able to identify separately.	Sec. 3.5

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3.8.2 How to Process Payload Data

Take the data received from transport and delivery, sometimes through the mission database, and construct the sensor information, which maybe an image, a spectra, or other meaningful product. This process transforms the data into a product usable by a discipline expert, as opposed to a sensor expert. You'll start processing payload data before launch and continue throughout the mission and often well past the end of the mission.

Payload data processing often occurs in a facility separate from the mission control center and under the control of scientists and specialists. Depending on the mission, organizations separate from mission operations may do some of this processing. Table 3.25 shows the steps for processing payload data. We discuss it in more detail in Chap. 13.

Table 3.25. Steps for Processing Payload Data. The steps will vary depending on the payload, but these are typical for scientific missions.

steps	Comments	Where Discussed
1. Validate Payload-Processing System	. Process data before launch from one or all of these sources: - Bench-level testing - System-level testing - Simulated data or real ground based data in a format similar to the flight instrument Note: Participation in system-level tests and end-to-end tests is helpful, but usually there are so many constraints from the non-space environment that the tests don't fully check out the processing capabilities. The "real" test often doesn't occur until after launch, when the instrument is in space.	Chap, 13 and 14
2. Generate Payload Data Records	• Data transport and delivery provides the payload data—either to the mission database or directly to the payload-processing facility-in the form of packets separated by instrument type . This data is then aggregated into payload data records—typically called level O processing .No value is addad to the data at this point It is the best set of data from the instrument that data transport and delivery can produce,	Chap. 13 and 14 sec. 3.4
3. Process Sensor-Specific Data	.Process instrument engineering data .Decompress data • Remove sensor signature .Apply calibration information to the raw data	Chap. 13
4. Correlate Ancillary Data with Sensor Data	:Add to the sensor-spec4flo data the ancillary data needed to process it into meaningful payload products	Chap. 13
5. Generate Products	.Generate a data record that contains the instrument data and its ancillary data with proper identification of the processing completed	Chap. 13

Table 3.25. Steps for Processing Payload Data. (Continued) The steps will vary depending on the payload, but these are typical for scientific missions

Steps	Comments	Where Discussed
6. Analyze Products	• Product analysis is usually separate from, but associated with, product generation • Before the data goes to the user, the operations staff makes sure it's meaningful and doesn't contain incomplete information or processing errors. This is especially true for scientific missions, in which the spacecraft is an observatory used by hundreds of astronomers.	Chap. 13
7. Manage Data	• Deliver products to the payload user or store them in a database for further processing and product generation • We need to manage data so we can locate for analysis products of the same region but taken at different times • The archiving function also uses data management	Chap, 13 See. 3.9

3.8.3   Products of Payload Data Processing

Although these products vary from mission to mission, Table 3.26 lists the most common ones. The objective of any mission is to obtain the sensor output, As we process data, we may detect deviations from the mission plan even when all other mission indications arc normal. The Viking project reached Mars and had to wait several weeks for a dust storm to diminish before mapping the landing sites and then landing on the surface. All engineering aspects of the mission were normal. Only the payload processing showed that the mission plan had to change.

Table 3.26. Products of Payload Data Processing. These are typical products for a scientific mission. Commercial and defense missions will have similar products, except for the press releases.

Product	Comments
Deviations from plan	• The mission plan describes the expected conditions. When these conditions aren't met, and sensor data isn't meaningful, users request changes to the plan.
Files of instrument calibration	• A separate fife usually records how data is recorded, so future users of the data may use different calibration techniques based on later information and understanding • Including this file and the data to which it was applied in the archival data records makes sure we don't lose information
Records of archival data	• The main product of this function ensures others can use the information for generations to come. The archival data record indudes the basic sensor data, the ancillary data, and the calibration files.

Table 3.26. Products of Payload Data Processing. (Continued) These are typical products for a
scientific mission. Commercial and defense missions 'will have similar products, except
for the press releases.

Product	Comments
Hard-copy products	.Hard-copy products are still used in many missions. Electronic ver-sions are becoming more common, but missions still use high qual-ity, specialized photo processing.
Press releases (for science missions)	.NASA missions use the output from payload processing to inform the public. Although military missions don't usually have press releases for their payloads, they do have similar requirements for briefings. .These products are for a specialized audience so they require a dif-ferent approach compared to those we use to understand informa-tion from payload sensors. We must understand these requirements early rather then after launch

3.8.4   **Key Considerations**

You can lower costs for processing payload data by addressing the topic early in the mission-concept study and then emphasizing them while developing the mission operations concept. During the MOS conceptual design (see Chap. 4), include these concepts for processing payload data:

> .Required final products
> . Diagrams of end-to-end data flow
> .The ancillary data required to process the payload data and its
>   sources
> .Robustness of the payload processing to data loss or drop out.
>   How will the proposed data compression and data formatting
>   react to the noisy environment?

The mission operations system can make the analysis more difficult if it loses, or doesn't collect, data. This means we need to pay special attention to the size, quality, and completeness of our ground system and how these characteristics will affect processing of the payload data. For many payloads, it's good enough for the ground system to complete 95% of the processing, but that depends on where the 5% loss occurs. Data lost as a block may be acceptable, but if the 5% loss is from compressed data across all the instruments, it maybe unacceptable.

When designing and doing payload data processing

> • Use Existing Tools. As discussed under payload planning and
>   analysis, using existing tools is an obvious way to save resources.
>   Within the scientific community, many payload users now take
>   advantage of standard processing packages.
> • Understand Requirements for Ancillary Data. Make sure you
>   understand and have available the ancillary data needed to

interpret payload data. If you discover after launch that this data isn't readily available, solving this problem will be expensive,

- .Ensure **Data** Processing Robustness. Understand early how well the system can process data without losses. Make sure it can transport data smoothly, taking into account such factors as data compression, data formatting, and the characteristics of the link performances. It is now common to simulate these characteristics early in the design phase to ensure the data-processing system is robust.

3.9 Archiving and Maintaining the Mission Database

The payload archive for processed data is usually separate from the mission database that supports controlling and acquiring mission data. But because these entities are closel y related, we treat them as one element of the MOS. The mission *database* receives, stores, and delivers data between the nine MOS functions. It can be centralized or distributed, usually receives data in real time, and can be accessed in either real time or in at some later time. The archive receives selected data for permanent storage and either immediate or historical review.

NASA scientific missions require the payload data to be archived so scientists other than the ones who designed the observation or built the instrument can use it. This data must be in a form others can use without specialized knowledge of the instrument. NASA archives cover several scientific disciplines.

The National Academy of Science did a study on archiving in 1986 and issued their recommendations in the CODMAC report [National Research Council, 1986]. NASA has followed several important recommendations in their archiving program. The report stressed that an active scientific archive should be located where scientists are using and improving the data, An example is the center for infrared processing and analysis on the California institute of Technology campus. This archive holds the data from the Infrared Astronomical satellite (IRAS), whose mission ended in 1984. The archive is still actively used. Another example is the Space Telescope Science Institute on the Johns Hopkins University campus. The science Institute holds the archive data from the Hubble Space Telescope. The mission is still in progress and will be past the end of the century. scientists around the world use this archive.

The mission database is the repository for all data collected and delivered to the project by data transport and delivery, as well as for data prepared for sending to that transport function. This database contains the controlled files of data required for processing the spacecraft data, plus the raw and processed spacecraft data. The database receives data in near-real time, but people in planning and analysis can use it at any time. Mission databases in the past have been centralized, but with today's technology, they're often distributed--around the world in some cases involving NASA scientific missions.

Active archives contain the instrument data generated during instrument testing and calibration before launch. They provide a valuable source of data for comparison with flight data. The degree of pre-flight testing varies from mission to mission but is often very extensive. After launch, they contain the data products sent to payload analysis from mission operations and the higher-quality data payload analysis produces.

Dormant archives store data from past missions that is either not used or very rarely used. Active scientists aren't at the storage location.

3.9.1   Information Required to Archive and Maintain the Mission Database

Table 3.27. **Information Required to Archive and Maintain the Mission Database. Archives enable use of the data long after the mission is over,**

Information Required	Comments	Where Discussed
Telemetry and tracking data	.The data received by the mission database is generally referred to as level 0. The mission dats base then processes and stores this data as leve 1, so we can use it to analyze the mission. .The level 1 data may also be part of the data archived.	Chap, 13 Sec. 3.8
Data from other functions in the mission operations system (MOS)	• Other MOS elements also generate data end store it in the mission database. Examples are command files and pass reports from mission control. .Certain of these products are also packaged into data to be stored in the archive. Analysis often requires engineering data to effectively understand the payload data. We may correlate this ancillary data to each payload product.	Sec. 3.1–3.8
Final payload products'	.Products the MOS generates for payload analysis-called level 3 data-are stored in the mission database and transferred to the project archive	chap, 13
Higher-level products from the payload	.Data processed by the payload centers-called level 4 data-are also transmitted to the project archive for use by others	Chap. 13

I **3.9.2 ,**   Process for Archiving and Maintaining the **Mission** Database

Table 3.28. **Process** for Archiving and Maintaining **the** Mission Database, The archive allows users to access data from previous missions and enables comparative analysis as well as more detailed analysis of the date

Steps	Comments	Where Discussed
1. Manage and Retrieve Data	• Acquire or receive the data from the mission database or payload users .Provide cataloging and retrieval, which references the data sets and allows retrieval by many different types of queries .Ensure the data received adheres to defined, agreed-to, standard formats	Chap. 13 sec. 3.8
2. Secure Data	• D–ate security is required as with the overall mission operations system • For scientific missions, we must give certain people access to some data for a time before it becomes available to other researchers. We call this data proprietary because it belongs to the scientist for a specified period	
3. Notify Users of Data's Arrival	. After placing date products into the archive, identity the new products and notify users of their availability .Usually automated for missions that generate large amounts of data	

3.9.3   **Products of Archiving and Maintaining the Mission Database**

Table 3.28. Products of **Archiving** and **Maintaining** the **Mission** Database. The products are date-and more **data.**

Products	Comments
Archived data	.At the top level, two types of date are in the archive: payload date and the ancillary data that describes its attributes. .Back up and store date in physically separate facilities
Operational data to and from functions in the mission operations system	.The mission database is a two-way database that allows the mission operations functions to share date and pass date from one function to another .The database is populated in real time, when we contact a spacecraft, as well as after the contact, when we add information received during the contact.

3.9.4   **Key Considerations**

The technology for archives and mission databases is changing rapidly, so our challenge is tcr keep up with the technology while efficiently and cost-effectively providing access to data. The medium of choice for many scientific missions is now CD-ROMs, whereas several years ago it was still tape. We also need to reconsider

the cost/performance ratio of delivering a data set by electronic means instead of by Federal Express.

Besides considering the technology issues in the mission operations concept (see Chap. 4), we also must ask ourselves how the data gets to the user? Does the archive send or does the user request? We must develop the archive plan, including the required ancillary data, as early as possible, so the ground team and spacecraft designers can more easily build a cost-effective archiving system.

3.10 Systems Engineering, Integration, and Test

These next four areas are most often on-going functions that apply equally well before and after launch. These disciplines appear in many fields, but we'll discuss only those which apply to mission operations.

The engineering function for the ground data system receives support from the nine MOS functions previously discussed. Thus, systems engineers understand the overall system and the interfaces, and each of the nine MOS functions provide details. Remember that what may be a sub-system at one level (e.g., the nine MOS functions) will appear as a system at the next level (e.g., activity planning and development). Thus, systems engineering occurs at all levels. But here we're talking about engineering of the mission operations system.

3.10.1   Information Required for Systems Engineering, Integration, and Test

Table 3.30. Information Required for Systems Engineering, Integration, and Teat. The information **listed enables this function to work across the nine main MOS functions from** which **it draws support,**

Information Required	Comments	Where Discussed
Project requirements	•Systems engineering keeps the project "vision"—making sure the data system and requirements satisfy this vision.	Chap. 1 and 4
Outputs from the operations concept	•Systems engineering uses these key outputs: - Operations scenarios - Derived requirements – Timelines - Data-flow diagrams	Chap. 4

3.10.2   Process for Systems Engineering, integration, and Test

Table 3.31. Process for Systems Engineering, Integration, and Test. These steps are typical for most missions.

steps	Comments	Where Discussed
1. Consider Typical Systerns Engineering Functions	. Consider these typical functions: - Develop system architecture - Generate, review, and control requirements - Define, document, and control interfaces - Monitor the application of standards, such as software walkthrough, which the project requires	Chap. 1 and 4
2. Integrate	• Usually (today-always), a different group of people does integration • Integrate the software programs and program sets into a system • Integrating software can be a large task depending on the complexity of the system being developed, or the multi-mission system being adapted for a new project • Validate the interfaces • Certify the system ready for operational testing, training, or use	Chap. 4 and 6
3. Simulate, Test, and Train People for the Mission	• Preparing simulations and testing can be as much work as carrying out the mission itself • Develop training plans • Develop simulation capabilities • Conduct training • Certify operational readiness	Chap, 4 and 6
4. Evaluate System	• Based on the mission operations concept, discussed in Chap. 4, develop and validate performance requirements • Test the MOS to verify that system performance meets requirements	Chap. 4
5. Ensure Network Is Secure	• Network security is becoming more important as the mission operations systems are becoming distributed and, in many cases, are using public networks • Write and implement the security plan; monitor the network	Chap. 12

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3.10.3   Products from Systems Engineering, Integration, and Test

Table 3.32. Products from Systems Engineering, Integration, and Test. Make sure all MOS people review and understand these products.

Products	Comments
System architecture	. In the system architecture, describe the vision of the sponsor and project management. Developing this vision early and keeping it updated are important because it provides a framework for daily decisions.
Specification of software Interfaces	. This specification is one of the most important products of systems engineering--especially if the project requires distributed processing or integration of the payload users' software into mission operations.
Integration and test plan	• 'The integration and test plan describes what to do when integrating new doliveries into the system. Having recursive tests and automated testing is important. Tools today allow even graphical user interfaces to be tested automatically, without a person sitting in front of a console.
Training plan	. The training plan developad for the mission operations manager allows mission operators to show they're ready for launch
Procedures	. Cover integration and test plus training
Security plans and tests	• Increasingly important, system security needs good plans and regular testing

3.10.4   Key Considerations

While the systems engineering processes of mission operations are not esrw-cially different from that of any large software system, the requirements are often fuzzy. They also change during the development cycle as the payload users learn more about what they really need. Especially on scientific missions, these payload users have a lot of power with upper management in the project and NASA. Thus, we must involve the payload users early and use rapid development and prototyping, rather than following the classic process of requirements, design, development, and delivery. Prototyping allows users to see capabilities.

The mission operations manager (MOM) should also

- Ensure the key concept trades for mission operations occur early
- Maintain the big picture
- Use rapid development and prototyping processes whenever possible

3.11 Computers and Communications Support

Designing and implementing mission operations hardware may involve staff within the project and from other organizations. For example, if the project uses an existing system, hardware development becomes a joint effort between the project and the organization that **owns** the basic system. Of course, the project manager must oversee hardware development by outside organization to make sure it operates properly. Other textbooks treat designing and building hardware for information systems, so we don't discuss it in detail in this book.

3.11.1   Information Needed to Support Computers and Communications

Table 3.33. information Needed to Support Computers and **Communlcatlons.** These requirements enable engineers to develop the hardware systems a mission needs,

Information Required	Comments	Where Discussed
Data-flow diagrams	• Develop data-flow diagrams first while developing the operations concept, as discussed in Chap. 4. Allocate processes to hardware and software at the same time, This is the starting point for designing the hardware.	Chap. 4 and 13
Requirements for computers or workstations	• Most mission operations now use distributed workstations or are moving toward them. • The number and location of the workstations depend on data flow, the mission operations architecture, and organization and staffing levels, Systems engineering typically specifies these requirements, • Many of the scientific missions have staff around the world who need workstations and, therefore, computer networking,	Chap. 7 and 8
Requirements for networking and data communication	• The specific and derived requirements for flowing data around the control center, country, or world demand much more networking and communications equipment. • Commercial open networks such as internet require attention to ensure that critical oommand and control have enough security to protect them from unauthorized users.	Chap. 13
Requirements for voice communications	• Voice communications and video-conference capabilities are important to understand early in the design phase. Designers often overlook these requirements, which are becoming much more important as we move from centralized to distributed control.	Chap. 9 and 12

3.11.2   How to Support Computers and Communications

Because these processes are typical for any computer hard ware, wc don't discuss them in detail.

Table 3.34. How to Support Computers and Communications. These steps are similar to those for any information system.

Steps	Comments	Where Discussed
1. Design and Build Computers and Communications Systems	• Understand existing capabilities and define what you must add to meet requirements • Get the data-system architecture from the EEIS engineer who helped develop the mission concept and from MOS engineers who helped generate the mission operations concept • Based on the hardware architecture and what you must add to the system(s), design and build the added capabilities • Test the mission operations system	Chap. 4
2. Maintain Computers and Communications Systems	• Maintain all computers and network equipment throughout the mission	-

3.11.3   Products from Computer and Communications Support

The products listed in Table 3.35 are again typical of hard ware in any informstion system.

Table 3.35. Products from Computer and Communications Support. The hardware and communications systems allow us to dovelop software and, later, carry out the mission.

Products	Comments
Computer and communications systems	• The ground hardware for mission operations
Networks and network access to functions of the mission operations system	• The networks and network access for mission operations • Identity open networks and those restricted for command and control functions
Voice-communication system	• The voice and video conference systems for mission operations

3.11.4   Key Considerations

Understand and include current technology in your design to get the best performance from hardware, Look at maintenance and its alternative sources to keep costs down.

3.12 Developing and Maintaining Software

We must develop and maintain soft ware throughout a project's life cycle:

- .The ground system before launch
- Software to correct errors after launch
- Software to capture changes in mission requirements after launch

On many of today's missions—especially interplanetary missions which take 2-10 years to reach the outer planets--we plan to develop more software capabilities after launch in order to make the mission successful. In some cases, mission operations people develop flight software before and after launch.

We must understand in advance how much development and maintenance will be necessary after launch, so we can organize and build procedures that will meet operational requirements.

3.12.1   Information Needed to Develop and Maintain Software

Table 3.36. Information Needed to Develop and Maintain Software. This information is typical for any software-development project.

Information Required	Comments
New requirements	• Most mission operations systems build on existing ones, but requirements will often emphasize new aspects of the system and be written as if nothing existed. Usually, we can refer to existing capabilities and documentation, but if you're asking for new capabilities, clearly state your minimum requirements,
Error reports	• Error reports start maintenance
Control authority for change	• To control costs, make sure your change authorizations are efficient. Deciding to approve a change after detailed design is done wastes resources.
As-built documentation	• An output of software development required for maintenance

3.12.2   How to Develop and Maintain Software

The steps listed in Table 3.37 are typical of any software-development effort. Many other texts discuss this development in more detail. For scientific space missions, requirements often aren't well defined, and the end user (often the scientist developing one of the instruments on the spacecraft bus) doesn't pay attention to mission operations until late in the development cycle. To interact with the scientist early and clarify requirements at the same time, try rapid prototyping or try delivering the ground data system in increments. The Mars Pathfinder project demonstrated data flow for downlink during concept development. They built on this capability in concept development, so a basic system existed when the project was approved.

Table 3.37. How 10 Davelop and Maintain Software. The mission operations manager must understand that developing a mission operations system mainly means developing a big information system with a lot of software.

steps	Comments
1. Manage Software Development	.Understand the requirements and ensure they are testable and agree with the mission operations concept .Develop the software; use rapid prototyping *to* ensure the system's users understand how fuzzy requirements will translate into hardware .Deliver the ground data system in increments . Plan for and understand that you'll be daveloping and maintaining software while the mission is operating .Ensure that schedules are compatible with schedules for developing and testing the spacecraft bus .Test the software-often it is developed in several increments .Deliver software to operations .Train on the new capabilities as required .Maintain the software
2. Maintain Software	. Changes to correct errors • Changes needed because mission requirement change

3.12.3   Products of Software Development and Maintenance

The outputs listed in Table 3.38 are typical of any software project.

Table 3.38. Products of Software Development and Maintenance.

Products	Comments
Plan for software development and maintenance	.The sponsor usually requires this plan, which document and communicate to the mission operations staff how the project will proceed
Schedules	.Schedules are a part of any software development. Make sure you understand the project schedules and how the software schedule supports the project's milestones: - Launch date - Date the mission operations system (MOS) must be ready - Start of MOS training - End-to-end tests of the system - System tests of the spacecraft bus
Test plans and reports	• These are required for any software development, but make sure you test interfaces and defined functions of a spacecraft or ground-system element that other agencies will supply
Working software and as-built documentation	.The result of the plans, schedules, and tests .Maintenance requires documentation .The level of documentation varies depending on whether the developers or a different organization does the maintenance
Reports of performance and errors	.Tracking of arrors and authorizing their fixes must be efficient

3.12.4   Key Considerations

This area is also rapidiy changing. What was developed as unique on the last mission may very well be available off the shelf as commercial software today. Understanding what is available commercially will save money and time. Looking forward—by trying to design software for reuse on future missions-is important. Finally, developers must communicate existing and planned capabilities to the system's users and operators, Find a way to involve them in discussions, reviews, demonstrations, and tests. Ask for their inputs. The earlier and more involved operators become with the users, the more operable the developed system will be.

3.13 Managing Mission Operations

Management functions for mission operations differ before and after launch. Before launch, we must develop and train so the entire mission operations system is ready for launch. Sometimes, one manager oversees both; sometimes, responsibility transfers formally from one organization to another. Names also vary depending on the organization. Before launch, the mission operations manager may be called the ground system or ground-data-system manager. At this point, the MOM works with other project functions to make sure operations are compatible with mission and spacecraft design. This process begins during the study phase and during development of the mission concept and the mission operations concept, but it continues throughout the development phase. After launch, manager names include mission director, mission operations manager, and chief of mission operations.

This section focuses on management functions unique to mission operations and discusses unconventional management practices.

3.13.1   Information Needed to Manage Mission Operations

Table 3.39 lists the information management needs to be successful. We use the first three inputs to guide development of the mission operations system. Before launch they guide changes to the mission activities that arise when status deviates from plans.

3.13.2   How to Manage Mission Operations

Table 3.40 lists management steps, all of which take place before and after launch. Before launch, we focus on developing the ability to support mission operations. After launch, we maintain the system, develop changes as required by changing mission conditions, and-- -on projects such as long planetary missions— finish developing capabilities needed to operate over longer periods.

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Table 3.39. Information Needed to Manage Mission Operations. This information enables the mission operations manager to make decisions during the mission

Information Required	Comments	Where Discussed
Requirements	Includes those placed on the mission operations system and those derived and generated by the mission operations system. The requirements not oniy are important for developing of the MOS but also aid operational decisions during the mission.	Chap. 1
Operations-concept	The operations concept is developed early in the iife cycle (study phase) and kept updated, This concept represents a common understanding between ail project people and the sponsor(s). Although the mission operations manager is key in generating the operations concept, it's also important to follow the concept every day.	Chap. 4
Sponsor's goals and vision	You must understand what your sponsor is expecting. How does he or she view schedule versus cost versus product quality? Can this project stand alone, or is it an enabling project for a new program? How does the sponsor view operational risk? The MOM's decisions and actions need to complement and enforce the sponsor's goals and vision.	Chap. 1 and 4
Status versus plans	After launch, managers must make operational decisions when deviations from plans or expectations occur. Understanding the current status versus the current pian is essential to making timely decisions.	sec. 3.1

Table 3.40. How to Manage Mission Operations. These steps are typical of those mission operations managers do. Each mission wiii emphasize certain steps.

Steps	Comments	Where Discussed
1. Define and Develop Operations Organization	• Generate and update the operations concept • Define an operations organization that minimizes interactions between groups and is process oriented • Define clearly the responsibilities for each position and make sure all members understand the operations organization • Monitor the organization's development as it matures • Make changes to improve the efficiency of operations	Chap. 4
2. Manage Interfaces	• Define each of the interfaces for the development organization • Define due dates for the receivables and deliverables that flow across the interface for each area • Manage the performance of the development areas by updating the receivables and deliverables schedule weekiy or monthly, as appropriate	Chap. 4

Table 3.40. How 10 Manage Mission Operations. (Continued) These steps are typical of those mission operations managers do. Each mission will emphasize certain steps

Steps	Comments	Where Discussed
3. Manage Change Control and Program Control	• Standard management texts describe these processes • Make sure the ground system evaluates tha effects of changes to the spacecraft bus before you consider them for approval	
4. Administer Contract Procurement	• Standard management texts describe these processes	
5. Manage Contin-" gency Reserve	• Before launch, include performance reserve for tools and processes, in addition to typical reserves for resource development • After launch, manage contingencies to ensure that added requirements fit within timelines and capabilities	Sec. 3.1
6. Manage Resources of the Mission Operations System (MOS)	• Manage these resources to meet mission objectives within the budget • Manage the MOS to provide a satisfactory return for a fixed or agreed-on cost. Five years ago, we managed the MOS to return the very best payload data.	Chap. 4
7. Manage Operations Schedule	• Manage daily activities' to use minimum staff while maintaining a proper and acceptable set of checks and balances • Ensure review and approval of planned command activities are at the fewest appropriate level and contribute value to the planned activity	Chap. 7
8. Manage Miscellaneous Activities	• Approve ad-hoc analysis and allocate resources to these activities • Manage development and ma intenance activities needed during operations • Develop processes for placing decisions into a risk matrix to make sure the risk isn't too high compared to the effect on cost or performance	

3.13.3   Products of Misslon Operations Management

The products of management aren't documents like those from many of the first nine functions. The management products listed in Table 3.41 keep mission operations focused on conducting the mission. Often, we can't analyze a problem for weeks or months before reaching a decision. We may have to decide in hours or days how to keep mission operations on track, despite problems or surprises.

3.13,4   Key Considerations

The mission operations manager must understand all aspects of the mission operations well enough to make effective decisions. For example automation and autonomy can save enormous costs during operation, so managers must understand how to use them.

**Table 3.41. Products of Mission Operations Management. The operations manager's most
important products are timely decisions and approvals**

Products	Comments
Project policies and guide-lines	• The management team, or the MOM, issues policies and guidelines during the mission • These statements encompass all aspects of the mission, but the focus is on guidelines that respond to changes in planned capabili-ties or performance
Decisions and approvals	• Decisions and approvals cover standard and non-standard aspects of the mission • Making timely decisions about problems or situations that arise dur-ing the mission is extremely important • Make sure an approval adds value to the product or recommended decision. The lower the level of approval, always considering risks to the project, the more efficient the organization
Reports and status to cus-tomers and sponsors	• The MOM reports upward and-outward • Sponsors and customers shouldn't be surprised by hearing about problems or successes from third parties • Make sure reports are meaningful and useful
Goals and visions of the project	• The mission operations manager's goals and vision are just as important to mission operations as the sponsor's goals and vision are to the mission operations concept

The operations staff at nearly all facilities and programs are being multi-
tasked. Specialized operational positions remain on only the most complex mis-
sions. A flat organization allows multi-tasking to take place more naturally while
also saving money.

Once you've established the first conceptual organization, identify the organi-
zational interfaces. What are the inputs and outputs of each organizational
clement and where do they begin or go to? If the diagram looks like a spider web,
you don't have an efficient organization.

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Developing a Mission Operations Concept

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> 4.1 Process for Developing a Mission Operations Concept
> 4.2 Steps for Developing the Mission Operations Concept

A *mission operations concept* describes-in the operators' and users' terms-the operational attributes of the mission's flight and ground elements. It results from the cooperative work of several disciplines. Its development is similar to that of a space mission concept, as discussed in Chap. 1, but the mission operations concept is more detailed and emphasizes the way we will operate the mission and use the space element (operational characteristics). It is generated in phases and becomes more detailed as our design of the operations system progresses.

The mission operations concept follows fron I, and is consistent with, the mission concept. It's the most important deliverable from the mission operations manager (MOM) before launch and is key to keeping system costs down. It's also the main way a MOM influences the design and operability of the mission and spacecraft. It often results in changes to the mission concept to reduce life-cycle costs. The MOM must understand what a mission operations concept is, how to develop one, and what it contains.

We generate a mission operations concept in ever more detailed layers, It doesn't detail a mission's development or operational costs, but it's primary to cost estimation. By combining the operations concept with assessments of operational complexity (Chap. 5), wc can determine the probable costs of operations early in mission design,

4.1 Process for Developing a Mission Operations Concept

Figures 4.1 and 4.2 show the process for developing a mission operations concept, along with the information it requires and its products. Table 4.2 shows the process steps and states where we discuss these steps further,
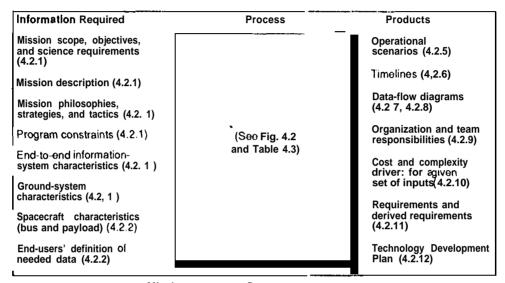
Information Required	Process	Products
Mission scope, objectives, and science requirements (4.2.1)		Operational scenarios (4.2.5)
Mission description (4.2.1)		Timelines (4,2.6)
Mission philosophies, strategies, and tactics (4.2. 1)		Data-flow diagrams (4.2 7, 4.2.8)
Program constraints (4.2.1)	(See Fig. 4.2 and Table 4.3)	Organization and team responsibilities (4.2.9)
End-to-end information-system characteristics (4.2. 1)		Cost and complexity driver: for a given set of inputs (4.2.10)
Ground-system characteristics (4.2, 1)		
Spacecraft characteristics (bus and payload) (4.2.2)		Requirements and derived requirements (4.2.11)
End-users' definition of needed data (4.2.2)		Technology Development Plan (4.2.12)

Fig. 4,1.   Developing a Mission Operations Concept. We describe the mission operations concept using a standard set of products,

Developing a mission operations concept requires different disciplines to communicate with each other. These disciplines include

- Designers of the mission, spacecraft, payload, and ground system
- Operators of the ground system
- Users (those who receive data from mission operations)

A space vehicle often operates differently from what its designers had in mind. This early communication between designers, operators, and users shortens the development time because fewer changes are required during development or testing,

The process emphasizes areas in these disciplines for which we should study trades to minimize life-cycle costs and get better information from the mission. The operations concept, when documented, provides derived requirements for developing functions of the mission operations system. Because the mission operations
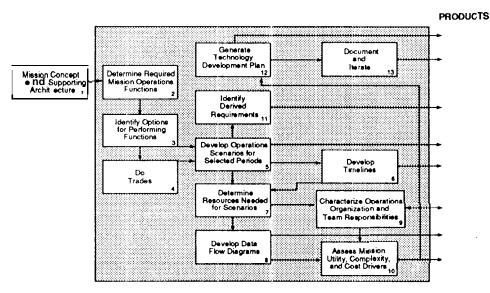
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PRODUCTS

Fig. 4.2.   **Process for Developing a Mission Operations Concept. The process is iterative and the products contain increasing levels of detail as we move from the study phase to the development phase. This process represents steps 6–8 in the process for daveloping a space mission concept, as described in Chap. 2**

concept responds to top-level mission requirements, we can easily trace these derived requirements to top levels while designing the mission. Each mission concept should have a corresponding mission operations concept. If we develop the two concepts in parallel, we can save time and shorten a project's conceptual and definition phases. That's because the mission operations concept can quickly feed back operational cost drivers into the mission-concept development.

To influence development, we need to complete the mission operations concept early, when the interfaces and attributes of the inputs are less defined and trade-offs are possible,

Completing the mission operations concept early often forces us to resolve design incompatibilities which operations developments or procedures would otherwise have to solve or minimize. Table 4.1 shows how required information solidifies during the project phases. Usually, by the time production and deployment begin, only the ground system, people and procedures, or flight software can change.

Because the mission is continually changing and maturing, updating the mission operations concept during the project is also important.

Chapter 3 describes the 13 mission operations functions. Eventually, people representing these functions need to help develop a mission operations concept.

Table 4.1.   Changes to Information Required for the Operation concept Versus Mission Phase, This table shows when inputs freeze within the project phases.

Information Required for Operations Concept	Project Phase				
	Needs Analysis	Concept Development	Detailed Development	Production and Deployment	Operations and Support
Mission scope, objectives, and science requirements	Changeable	Changeable	Changeable for cause	Frozen	Frozen
Mission description	Changeable	Changeable	Changeable for cause	Frozen	Frozen
Mission philosophies, strategies, and tactics	Changeable	Changeable	Frozen	Frozen	Frozen
Program constraints	Changeable	Changeable for cause	Frozen	Frozen	Frozen
Characteristics of the end-to-end information system	Changeable	Changeable	Changeable	Existing frozen; New changeable for cause	Existing frozen; New changeable for cause
Capabilities and character-istics of the ground system	Existing frozen; New changeable	Existing frozen; New changeable	Existing frozen; New changeable	Existing frozen; New changeable for cause	Existing frozen; New changeable for cause
Spacecraft capabilities and characteristics (bus and payload)	Changeable	Changeable	Changeable for cause	Frozen	Frozen
Flight software	Changeable	Changeable	Changeable	Changeable for cause	Existing frozen; New changeable for cause
End-users' definition of needed data	Changeable	Changeable	Changeable	Frozen	Existing frozen; New changeable for cause

Often, in the early phases (conceptual), one person will represents everal func-tions. One representative will usually lead discussions and keep the concept. This person often comes from the system engineering or mission planning functions and typically has experience working with information systems.

Because the mission and mission operations concepts are closely linked (see Sec. **4.2.5),** some people participate in both activities. Table 4.2 relates the mission operations functions described in Chap. 3 to the main engineering discipline involved in developing them and to the inputs to and outputs from the mission

operations concept. This table follows the order of putting products into the mision operations concept, as shown in Fig. 4.1.

Table 4.2, Providers of Information Required to Develop a Mission Operations Concept, Functions of the Mission Operations System (MOS) are listed in the order they are needed. Products indude use and description of new or existing capabilities, timelines, and requirements and derived requirements for each function.

MOS Function	Discipline	Information Provided by MOS Function	Where Discussed
Mission planning	Mission-planning engineer	• Mission scope, objectives, and payload requirements , Mission description • Mission philosophies, strategies, and tactics	sec. 3.1
Managing mission operations	Project manager	• Program constraints and requirements • Sponsor's goals and vision	Sec. 3.13
Systems engineering, integration, and test	End-to-end 'information systems engineer Ground data system engineer	• EEIS characteristics • Characteristics of GDS	Chap, 6, 11, and 12 sec. 3.10
Payload planning and analysis	Payload designer Payload-operations engineer	.Payload characteristics .Payload operations	Chap. 8 and 4 sec. 3,7
Payload data processing	End-users (recipients of the data products)	• Data-product definition • Payload operations	Chap. 8 and 13 Sec. 3.8
Spacecraft planning and analysis	Spacecraft designer Spacecraft operations engineer	• Spacecraft character sties • Spacecraft operations	Chap. 8 and 15 Sec. 3.6
Activity planning and development	Sequence designer and operations engineer	.Mission plan .Mission rules .Test and integration requirements	Chap. 7 and 8 Sec. 3.2
Mission control	Mission-control designer and operations engineer	• Mission plan .Mission rules	Chap. 8- sec. 3.3
Data transport and delivery	Data-transport designer and operations engineer	• GDS capabilities .User requirements .Data format and volume	Chap. 11 and 12 sec. 3.4
Navigation planning and analysis	Navigation designer and navigation operations engineer	• GDS capabilities .Requirements for trajectory and attitude data	Chap. 8 and 10 Sec. 3.5

Table 4.2. **Providers** of Information Required to **Develop a Mission** Operations concept. **(Continued)** Functions of the Mission Operations System (MOS) are listed in the order they are needed. Products include use and description of new or existing capabilities, timelines, and requirements and derived requirements for each function.

MOS Function	Discipline	information Provided by MOS Function	Where Discussed
Archiving and maintaining the mission database	Archive designer and operations engineer	.GDS capabilities .User requirements .Data format and volume	Chap, 8 and 13 sec. 3.9
Computers and communications support	Computers and communications engineer	.Data-flow diagrams .Computer, network, and voice requirements .GDS capabilities	Chap. 11 sec. 3.11
Developing and maintaining software	Software-development engineer	.Software requirements .Existing software capabilities .Change control authority	Chap. 6 Sec. 3.12

4.2 Steps for Developing the Mission Operations Concept

Figure 4.2 diagramed how to generate a mission operations concept; Table 4.3 lists the major steps. We describe the process in detail below.

Table 4.3. Developing a Mission Operations Concept. This table expands Fig. 4.2 by identifying key items and pointing to chapters with additional information.

step	Key items	Where Discussed
1. Identify the mission concept and supporting architecture; gather information	.Characteristics of information system .Characteristics of payload . Characteristics of spacecraft bus .Definition of data product • Ground system	Chap. 1, and 2;
2. Determine functions needad for mission operations	Key functions usually vary for each mission concept and related architecture. You can combine or eliminate some functions	Chap. 3
3. Identify ways to accomplish functions and whether capability exists or must be developed	.Where accomplished (space or ground) .Degree of automation on ground . Degree of autonomy on spacecraft . Software reuse (space and ground)	Chap. 1, 2, and 3
4. Do trades for items identified in Step 3	Options are often selected before developing operational scenarios. These trades are done within the operations element which includes the flight software.	Chaps, 1,2,3,4, and 5 Table 3.1

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Table 4.3.   Developing a Mission Operations Concept. (Continued) This table expands Fig, 4,2 by identifying key items and pointing to chapters with additional information.

Step	Key Items	Where Discussed
5. Develop operational scenarios for the functions determined in Step 2 and the options selected in Step 4.	*Operations scenarios* are step-by-step descriptions of how to do integrated activities. Identify key issues and drivers on the operations system.	Chap, 4, 6–8
6. "Develop timelines for each scenario	Timelines identify events and how fast and when they occur. They drive the performance parameters for each mission operations function.	Chap. 4, 6–8
7. Determine the type of resources needed to perform each step of each scenario	The allocation to hardware, software, or people is based on what, how quickly, and for how long steps must be done.	Chap. 4
8. Develop data-flow diagrams	Data-flow diagrams form the basis for the ground- and flight-date systems and the command, control, and communications architecture.	Chap. 4 and 13
9. Characterize responsibilities of the organization and team	Identify organizations involved and their structure, product responsibility, interfaces and number of people, For cost-effective operations, minimize the number of organizations and interfaces.	Chap. 4 and 5
10. Assess mission utility and complexity, as well as the cost of mission operations	The cost estimates include both development and operations costs. Refine them each time the mission operations concept is updated.	Chap. 5; Chap, 3 and 20 [Larson and Wertz, 1992]
11. Identify derived requirements - and cost and complexity drivers; negotiate changes to mission concept if necessary	Document derived requirements and ensure consistency with top-level requirements	Chap, 1,2, and 4
12. Generate technology development plan	The technology to support the mission concept may or may not exist	Chap. 6 Sec. 4.12
13. Iterate and document	Iteration may occur at each step	-

4.2.1   Identify the Mission Concept and Supporting Architecture

We begin developing the mission operations concept by examining the mission concept and supporting architecture. By obtaining the information listed below, or by making assumptions, we can describe the mission in users' and operators' terms. When information is not available-the design is not yet started or not specified in the mission architecture-the operations-concept team assumes information and gives this input to the person responsible for it. The operations

concept is **then valid until the assumed information changes.** We can **determine the cost of this** change **by modifying the operations concept as required and then rc-evaluating the complexity and** cost of the mission operations using the model described in Chap. 5.

Mission Scope, Objectives, and Payload Requirements. Wc must state mission objectives in terms of data the payload can get through effective operations. These objectives capture what the spacecraft must do to achieve the mission's scientific, commercial, or defense goals. This input defines and describes the users of the payload data and their level of sophistication. Our system will be different for a scientist who can use state of the art computer tools for analysis versus a politician who wants to access information from the Earth Observation System. We need to know how people will use the payload's processed data. Potential uses are research, commercial, defense, education, or public information. We also need to know the timeliness requirements for the payload's processed data and the success criteria (percentage of total data actually returned).

Mission Description. This input contains information about the trajectory, such as launch date(s) and window, trajectory profile, maneuver profile needed to meet mission objectives, mission phases, and a description of activities required during each phase. Observation strategies describe how we'll gather the mission data, We either define and finalize the observation strategies and mission description before launch or adapt them to data gathered during the mission.

Mission Philosophies, Strategies, and Tactics. These items are rules not associated with the health and safety of the mission. They may relate to the mission objectives or to the background of the mission designers and those developing the mission concept. It's important to try to determine if the itcm is associated with the mission or a person's preferences.

Examples are

- . Maximize real-time contact and commanding versus maximize onboard autonomy and data-storage capability
- Maximize the involvement of the educational institutions and teach science students key aspects of issues like operations or space physics
- * Make sure a central authority approves all commands
- Limit the image budget to 50,000 images

Program Constraints. The sponsor of the mission and the project manager impose these non-technical constraints. Operators must follow them until the project manager is convinced they are increasing the cost of the mission. Examples of program constraints are

- Limit mission cost and cost profiles
- Use a specific tracking network
- Use existing flight hardware

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' • Use existing ground-system capabilities and design the spacecraft to
        be compatible with them
  . Centralize or distribute operational teams
  .Use multi-mission versus project-dedica ted teams
  . Involve students versus dedicated professionals
  • involve educators and the educational community

Capabilities and Characteristics of the End-to-End Information System
(EEIS). The EEIS engineer will have helped develop the mission concept, which
will describe the spacecraft and ground elements in terms of information flow and
processes. System-level requirements include

  • Using information standards (layered protocols or CCSDS standards)
  .Locating capabilities and processes (includes both space and ground)
  • Characterizing the information system's inputs and outputs

The EEIS engineer specifies these requirements in terms operators and users can
understand, not in terms used by computer scientists and programmers.

Capabilities and Characteristics of the Ground Element. Most missions are
designed around a specific agency's ground system, such as the AFSCN, NASA,
or European Space Agency. Each ground system has standard services which will
support the mission at low (or even no) cost if the mission meets specified inter-
faces and standards. We follow these requirements on the flight system until they
keep us from meeting mission objectives. We must ask

  • What standards does the ground system require the spacecraft to
      meet ?
  . How do we carry out the standa rd and what requirements does this
      place on the spacecraft?

Some standards, such as CCSDS, are broad and allow for interpretation. Thus,
wc can meet CCSDS standards for telemetry and commanding but choose a way
of meeting them that our ground system won't support.

4.2.2   Determine Functions Needed for Mission Operations

The mission concept drives top-level functions, but the spacecraft's capabili-
ties determine the detailed ones we must carry out, A completely autonomous
spacecraft requires few operations, whereas a spacecraft payload that can't com-
pute or store data onboard requires continuous ground control or ground
automation. Thus, to determine what we must do, we have to understand the
spacecraft's characteristics. The mission concept may state these characteristics if
the mission concept team includes operators. Otherwise, we'll develop them as
part of the mission operations concept. Through discussions, the operators and
developers define the characteristics described below.

Capabilities and Characteristics of the Payload. Including payload designers and mission planners in the mission-concept process leads to timely definition of the payload characteristics. People working on the concept need to develop information that answers the types of questions we've asked below. These questions come from past missions and often start payload designers thinking early about how the payload will operate and the differences between testing it on the ground and operating it in space.

To understand how a payload will operate, we must describe what the payload will do during an observation period.

- What arc the payload's attributes?
- What is the commanding philosophy? Is the payload commanded by using
  - Buffers?
  - Macro commands?
  - Tables?
- Dots the payload usc default values?
- Will some commands degrade or damage the payload?
- Do some mechanisms depend on previous commands?
- Dots the payload usc position commands or incremental commands to control rotating or stepping mechanisms?
- What classes of commands dots the payload USC?
  - Real-time?
  - Stored program?
- What processing occurs within the instrument?
- How can we describe the payload in terms of
    CPU/Memory?
    Closed-loop functions?
    Predictive commanding versus event-driven commanding?
    Requirements placed on the spacecraft bus for instrument control?
    Mechanical power and thermal attributes?
    Avoidance areas (Sun, Earth, South Atlantic Anomaly, Venus, or Moon)?
    Requirements for controlling the spacecraft bus?
- Are the payload apertures larger than the spacecraft bus's pointing control?
- What are the user-specified parameters for observation?
  - How are these converted into instrument commands?
- What is the instrument heritage?

.What ground processing and analysis is required to support the instrument's operation?

The above questions may seem obvious, but they come from missions in which the spacecraft had been designed and, in some cases, built before anyone asked them.

The example below shows how considering the payload's operation will help us define the mission concept.

An instrument is designed with an aperture that has a field of view of ten arc-seconds. At the same time, the spacecraft designers have designed a spacecraft bus that has a control authority (the ability to point with a certain accuracy) of 20 arc-seconds. The operators can never be sure the celestial object they command the spacecraft bus to observe will capture the object in the instrument's field of view. The solution was to

- **Command the spacecraft to the desired position**
- **Observe with a different instrument that** has a wider field of view and see how far the spacecraft is off from the desired position
- Generate attitude commands to move the spacecraft just a bit (tweak commands) until the actual attitude corresponds to the desired attitude
- Verify the attitude errors are gone
- Select the instrument with the narrow aperture and observe as specified

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This one design issue caused real-time operations, decision making, and commanding to be routinely involved for this mission. This involvement required more ground software, controllers trained in routinely commanding the attitude-control system, and more people whenever the instrument was used. The goal of generating a mission operations concept is to identify incompatibilities and cost drivers early, before designing and building any hardware.

It's a good idea to ask the designer of a payload instrument how you'll go from an observer's requirement to a set of commands for the instrument. Sometimes, the answer is simple, but in other cases instruments that have been designed for a laboratory rather than for space. Let's look at another example and the process is complex.

An astronomer knows the celestial object we need to observe and its estimated brightness within the wavelength we'll look at. A spectrometer is the specified instrument. What must the operations staff do to generate the commands for this observation?

- Make sure the previous observation has an intensity lower than the one we'll observe
- Add a calibration before the observation

- - If the observation **is longer than five minutes, add short**, internal, **calibrations** every five minutes until the observation is complete
- Add a calibration after the observation

This instrument design requires us to sort the observations and do them in order of increasing intensity, even though it may not be the most efficient way to move the telescope from one object to another.

For this design, the astronomer's requested observation time drives how long we must look at the object, which in turn determines the total number of commands our spacecraft requires. Also, until we've established the instrument's characteristics in space, we can't set the calibrations and durations. So we'll probably need to recalculate after launch.

Capabilities and Characteristics of the Spacecraft Bus. As is true for the payload's capabilities and characteristics, timely definition of the spacecraft's characteristics depends on including spacecraft designers and mission planners in the mission concept process. Again, people working on the concept have to answer the following types of questions for the overall spacecraft and its subsystems:

- What are the spacecraft's operational attributes?
  - What commands and parameters are sent from the ground?
  - How are the values of these commands determined?
  - How many commendable states are there?
  - Are engineering calibrations required? What are the purpose, frequency, and schedule constraints of the calibrations?
- How many engineering channels need monitoring?
- Do these channels provide subsystem-level information to the operators, or must operators derive information about subsystems?
- For the attitude-control system
  - Are guide stars used? If .s0, how are they selected?
  - How does the pointing-control accuracy compare to instrument requirements?
- What types of margins exist and what must be monitored and controlled?
- What expendable need monitoring during flight?
- Does the spacecraft subsystem use any onboard, closed-loop functions?
- What are the attributes of the spacecraft's data system?
- What processing must we do on the ground to support spacecraft operations?
- What is the heritage for each of the spacecraft subsystems?

Consider an example of how a design decision affects operations.

The Galileo spacecraft was designed to take heat from the Rad ioisotopic Thermoelectric Generators (RTGs) and use it to warm the propulsion system. This design saved weight and power and cost less to develop. But the spacecraft's operational characteristics tied together subsystems for propulsion health and safety, thermal transfer, and power. Operators had to check each command load to see how it changed power states and affected the propulsion subsystem. Engineers from power, thermal, and propulsion had to check each sequence, even if only the payload instrument's states changed. For example, turning an instrument off (or on) caused the heat output of the RTG to change.

End-Users' Definition of Needed Data. End-users inform mission operations by defining how, and how often, they will use data from the payload. By understanding these data products, ground-system engineers can start designing how they'll get them.

We must understand how confident the end-users are about the products. Often, they don't know what they want until they see how the instrument works in flight and what it observes. In these cases, engineers can prototype processes before launch and finish them after launch, once definitions are complete..

We also need to define the products' relationship to the payload data by answering the following questions:

- Is **the** product based on the payload's raw data or must we remove the payload instrument's signatures?
- Must the data be calibrated? How? Does it involve processing special calibration observations? At what rate do we expect the calibration files to change?
- Does the data need to be converted into geophysical units? How? Where do the algorithms for this conversion come from? Must the project generate them and update the mission database as they become more refined?
- What are the formats and media of the payload's data products? Is there a community standard, such as the Astrophysical community's use of an Flexible Image Transport System (FITS) format on all of NASA's astrophysics missions?
- What ancillary data must we provide so the end-user can interpret the payload data?
    – Spacecraft position?
    - Spacecraft attitude?
    – Ground truth data?

- Who processes the payload data?
    - Project ?
    – End-user?
- How does the processed data get into the archives?
    - Through the project?
    – Through the end-user?
- What, if anything, must the project archive after the flight phase is over?

Generate a List of Top-Level Functions Operators Must Do. Referring to Chap. 3, we can address each process within the 13 operational functions to generate this list using the information we've developed in Sec. **4.2.1** and 4.2,2. When time constraints or requirements are available, we may add them to our early design of a mission operations system for a given mission concept.

4.2.3   Identify Ways to Accomplish Functions and Whether Capability Exists or Must Be Developed

At this level, many steps-and the ways to do them—will be straightforward. For example, to track an interplanetary spacecraft, we use NASA's Deep Space Network. For other steps, we'll have to identify several options and describe them. For example, to determine a spacecraft's orbit, we might use global-positioning satellites and automated procedures onboard, or we might track the spacecraft and calculate its orbit on the ground,

To understand options, try building a table which contains the operations functions that apply to the mission's database and avionics, Then, identify whether the avionics (automated) or the ground system will do each function. If on the ground, further determine whether the hardware, software, or operators will complete it. If a check goes in more than one place, describe which functions are done in each plain and whether options exist. Table 4.4 shows how such a table would look.

If the ground hardware and software do something, ask, "Could the avionics partially or completely do this function and lower the mission's life-cycle costs?" For example, if you were considering orbit determination, you'd ask, "Could we plan and analyze position location within the avionics?" Then, you'd look at the accuracies of the GPS system, check the cost of GPS receivers that are flight qualified, and do a first-order estimate of the change in life-cycle costs. Don't forget that the costs of tracking facilities are important in this type of trade.

4.2,4 Do Trades for items identified in Step 3

For the options identified in step 3 that will drive either performance or cost, a small group of engineers needs to do trades and decide how to carry them out,

Table 4.4. **Identifying Where to Carry Out Functions. Using a table similar to this one will help the MOM identify options for carrying out mission operations. We assume functions not included in table are done on the ground. As you evaluate each function, place a check mark in the table to indicate when you accomplish the function.** _cehere_

| | Where to Do the Function | | |
MOS Function	Avionics	Ground Hard"ware/ Software	Operators
Activity planning and development			
Mission control		—	
Data transport and delivery	—		
Navigation planning and analysis			
Spacecraft planning and analysis		— — —	
Payload planning and analysis		— —	—
Payload data process-ing			— — —

In some cases, engineers may develop an operations scenario for each option to describe it in detail.

4.2.5 **Develop Operational Scenarios**

Operational scenarios are key to an operations concept. A scenario is a list of steps and we can describe an operations concept with about a dozen top-level scenarios. Typically, planners generate three types of scenarios during study and design, with each increasing in detail:

- .User scenario
- •System scenario
- •Element scenario

Each of these scenarios has a corresponding timeline and data-flow diagram, as discussed in Sec. 4.2.6 and 4.2.8.

During the early study phases of a mission, users develop a scenario to show how they want to acquire data and receive products from the payload. For a NASA mission, the user would be the principal investigator or science group or, for a facility spacecraft such as the Hubble Space Telescope, an individual observer.

We create a system scenario after we've developed the operations architecture—during the operations-system design, Here, we emphasize the steps within

a process needed to conduct the mission. Finally, during element design, we expand these system scenarios to include more detailed elements and subsystems.

The mission concept, mission operations concept, and design of the space and ground elements are closely related. As design proceeds, costs are always in planners' minds. The cost of development and operations are both important, so we must estimate them during study and design. As designs for the space and ground elements mature, we have to do trade studies to get the lowest cost and best design within some cost cap. Whenever we expect to exceed this cap or believe we can reduce costs by changing the mission concept, we study possible mission trades. Figure 4.3 depicts this process.
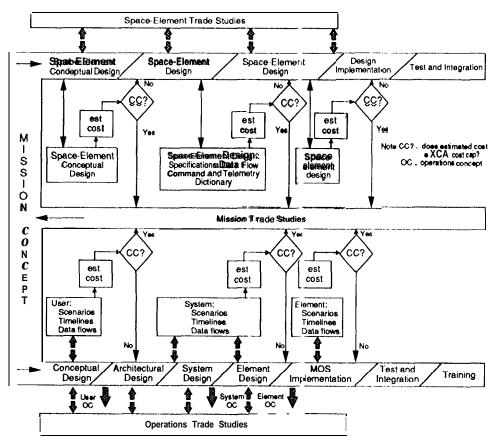

Fig. 4.3.   **Trade Studies for Mission Operations and Space Element.** Designing to cost requires frequent cost estimates and trade studies within mission operations and the space element,

Typical operational scenarios, along with questions to ask or items to include, appear below.

Develop a scenario for total mission based on the trajectory and the mission goals. Define the trajectory in terms of activity periods and mission phases. (See sec. 3.1)

- Launch
- Spacecraft bus checkout
- Payload checkout
- Key payload periods, data gathering, and inactive or quiet periods
- Maneuvers
- End of mission

For each phase specified, describe in words the steps (inputs, processes, and outputs) required to go from the user(s) request for an observation to the payload's acquisition of requested data. Also address how you'll handle review and approval.

The scenarios discussed below arc part of uplink:

How Does User(s) Plan the Request? A typical request from an astronomer could be: Use a particular instrument to observe a celestial object with an estimated flux and located at a given position; obtain a 4x4 mosaic image.

- . What parameters are used to describe the request?
- . What tools are required to help the user make the request?
- Where is the user?
    - At the control center?
    - At a remote site?
- What are the form and content of the request?
- . Is the request part of a mission plan that has constrained the user?
- . How does the mission operations system support the user?
- . What type of user(s) are involved in the mission?
    - Single user?
    - Multiple users?
- Where and how is the request is delivered?
    - Spacecraft?
    - Activity planning group?
    - Mission control?

For many missions today, users stay at home but submit requests to the control center. Commands are interactive or non-interactive. The non-interactive commands don't need monitoring or checking. The control center can create and send them directly to the spacecraft during the current or next track.

How Are the Activity Requests Integrated? Integration resolves conflicts among users, tracking facilities, and spacecraft resources. Fewer requirements for integration mean lower costs plus shorter and more adaptable sequences.

- .Who is requesting the activity?
- • What are the relative priorities for these requesters?
- • Where do inputs come from?
    - - User(s)?
    - – Mission control?
    - – Spacecraft analysts?
    - - Payload analysts?
- • What are the flight rules?

The spacecraft and payload designers should list flight rules they expect activity planners and developers to validate before sending commands to the spacecraft.

How Are the Integrated Requests Converted to Command Mnemonics and Binary Files? We may need to create one command for each activity, or we may need to expand blocks into many commands, We also must describe how to generate and maintain the command dictionary that will control all conversions.

How Are the Binary Files Wrapped with Ground and Spacecraft Protocols and Transmitted to the Spacecraft? Getting messages from the ground to the spacecraft will be more difficult if the ground system uses a standard that the project hasn't imposed on the spacecraft.

- • Who is responsible and what steps are required to get the commands into the spacecraft?
- . What steps will get the commands from the control center to the tracking station?
- • What ground resources are used for this transmission?
- • What are the uplink characteristics?
    - – Frequencies?
    - - Command rates?
- . What are the allowable bit and expected-error rates?

We have now transitioned into activities that occur onboard **the** spacecraft:

How Does the Spacecraft Receive and Verify the Command Files and Store or Execute the Commands?

- . What are the interfaces and processes between the spacecraft's avionics system and the payload's data system for various commands?
    - – Immediate execution?

- Stored commands (within the spacecraft)?
- Commands stored by the payload instruments?
- How are the commands verified?
    - Command receipt?
    - Command execution?
- Is the verification real time or delayed?
- Who supplies the information which will enable the commands to be verified?

The following scenarios are for downlink—relaying data from the payload to the recipient:

What Are the Processing Functions and Interfaces From Payload to User?

- What happens to the data as it goes from the payload instrument to spacecraft storage?
    - Is the data compressed?
    - What arc the payload output rates?
    - How does the spacecraft collect the payload data? Synchronous or asynchronous?
    - What type of storage is used? (Solid-state memory is replacing tape recorders on most missions.)
    - What are the storage and retrieval characteristics? Is the data retrieved by location or by a request for a file?

Today most data is retrieved by location or first-in, first-out (FIFO) from an area of storage. The next generation of missions will store and retrieve data by files, just as we do today on our personal computers.

- What happens to the data as it goes from the storage area to the spacecraft transmitter?
    - Is the data encoded to improve signal-to-noise characteristics of the link? If so, what type of encoding?
    - Is the data encrypted for security?
    - What transmit rates are available on the spacecraft?
    - Can stored data be transmitted at the same time as real-time data?
- How do we transmit data to storage in the ground database (level O processing)?
    - Must the spacecraft or spacecraft antenna be pointed prior to transmission? How?
    - What transmitter and receiver characteristics determine the link performance?

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- With these characteristics plus the encoding, what are the error rates and allowable data-transmission rates?
- What are the transmission rates for the various mission phases?
- What arc the processing and storage steps from receiving data at the ground station to storing this data in a project database?

We have now transitioned from the spacecraft to the ground system

. What steps are necessary from receiving the data in the project database to having the content ready for delivery to the end user? We must specify processing volume and speed to properly size the system-usually an extensive section that's different for each mission.

How Is the Data Formatted, Analyzed, and Delivered to Meet the User's Requirements?

.What data must we analyze in real time for
-- Health and safety?
- Payload quality?

.What data must we analyze later to
- Control the mission?
- Determine quality and content of payload data?

How Is the Data Archived? What processing must we do to meet the requirements for

- Format?

.Quantity, quality, and continuity?

.Frequency of updating the archive?

How Does the Processed **Data** Change the Mission Plan or Activity Plan? **(Closing the Loop)**

.How is the processed data compared to the mission plan?

.What are the criteria for changing the mission plan?

.How do we change the plan changed?

.How do we deliver the modified plan to the operations-system element for implementation?

How Does the Payload-Calibration Plan get Generated, Verified, and Modified?

.What is the payload-calibration plan?

. How are descriptions of calibration activities generated? Is specialized software necessary? Does the payload instrument have special modes only for calibration?

·How arc the calibration observations analyzed? By whom? How
fast?
·How arc new observations generated?

What Are the Scenarios for Top-Level Contingencies? These scenarios
address what happens when spacecraft-bus or payload anomalies occur. We must
assign categories of anomalies, primary responsibility, (ground or space element),
and required response times.

Other scenarios may be helpful. Use your imagination and knowledge of your
mission to develop them.

4.2.6   Develop Timelines for Each Scenario

Now you can add times needed to do each set of steps and determine which
steps can be run in parallel or must be serial. This information becomes a source of
derived requirements for the mission operations system's performance.

Various agencies, universities, and companies own timeline tools. There are
no standard tools, but many are modified from commercial, off-the-shelf software.
Most missions use the same timeline tools for operational scenarios and activity
planning.

4.2,7 Determine the Types of Resources (Hardware, Software, and People) Needed to Perform Each Step of Each Scenario

Once you've developed scenarios you may assign machines or people to do
each step. This choice will be obvious for many steps, but others may be done by
people or machines, depending on performance requirements and available
technology.

Having allocated resources, turn steps assigned to hardware and software into
data-flow diagrams. For steps assigned to people, develop an operational organi-
zation and assign steps and functions to teams.

At this point, you should examine each step to which you've assigned an oper-
ator and ask, "Can this process be automated to eliminate the operator? How?"
Allow a person to do something only when life-cycle costs mandate human
involvement, Don't accept the idea that we need a person because we've always
done it that way. Technology is advancing so rapidly that a machine may very well
do now what a person had to do on the last mission.

Through this process, you'll also discover areas on which to focus R&D fund-
ing for possible automation in future missions. This concept of "justified
operation" was developed at a NASA workshop held in January, 1995. [NASA,
1995]

4.2.8   Diagram Data Flow

System-engineering tools can convert your machine steps into data-flow diagrams showing processes, points for data storage, and interrelationships.These tools also generate a data dictionary which ensures a unique name for each process or storage point in the data flow. These computer-aided systems engineering *(CASE)* tools then generate information you can use for development.

4.2.9 Characterize Responsibilities of the Organization and Team

Once you've defined processes, gather the people steps and form an organization around them. Assign teams to the steps and analyze the organization to establish operational interfaces. Generally, the more inputs required from different teams, the more complicated, costly, and slow the operations organizations will be.

4.2.10 Assess Mission Utility, Complexity, and Cost Drivers of Mission Operations

Chapter 5 describes methods and concepts for identifying mission complexity and cost drivers. Development and operations (post-launch) costs for a given set of inputs are key aspects of an operations concept. Chapter 3 describes the top-level cost drivers for the 13 operations-system functions.

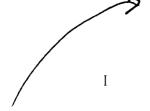### 4.2,11 identify Derived Requirements

Relate the scenarios we've described to the top-level requirements. You can then use the steps within a scenario as the source of derived requirements. The operations concept is a good place to keep and document the relationship between the top-level requirements and the derived requirements related to these scenarios.

4.2.12 Generate a Technology Development Pian if Appropriate

The technology to support a mission concept may not exist or may not be focused and prototype to a level that is appropriate for the mission approval. Identifying the technology needed to support a mission operations concept, along with the schedule and needed funding, is an important output of generating the mission operations concept.

4.2.13 iterate and Document

Document results of your effort to develop an operational concept so others can benefit from your information. Following is a suggested structure for this document. While developing the concept, keep this information in electronic form and available to all members of the project, so people can review and critique it.

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.Inputs
.Scenarios
> Describe operational scenarios-those listed in this chapter or more detailed ones based on them

I

. Timelines
.People and procedure functions
- Organization and team responsibilities
.Hardware and software functions
- Data-flow diagrams
. Requirements and derived requirements

The mission operations concept is the operations manager's most important product before launch. It enables the manager to discuss changes to the mission concept based on quantitative data. The earlier the first mission operations concept appears, the greater the leverage for minimizing life-cycle costs. It's important to keep the mission operations concept current because it's the best top-level description of how the mission will be flown and the tools we need to fly it.

References

Future NASA Miniature Spacecraft Technology Workshop. Feb. 8- 10,1995. Pasadena, CA.

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